ISSN 1173-5996

CLASS A FOAM WATER SPRINKLER SYSTEMS

BY

David B Hipkins

Supervised by

Dr Charley Fleischmann

Fire Engineering Research Report 99/9
March 1999

This report was presented as a project report
as part of the M.E. (Fire) degree at the University of Canterbury

School of Engineering
University of Canterbury
Private Bag 4800
Christchurch, New Zealand

Phone 643 364-2250
Fax 643 364-2758

ACKNOWLEDGEMENTS

My sincere thanks to my employer, Tyco New Zealand Limited, for having the foresight to invest in the higher education of their employees.

To all my colleagues in the Tyco organisation, world wide, who assisted with professional advice and who rummaged through libraries to source references. A special word of thanks to Joe Behnke and Mitch Hubert (Ansul, Marinette), Jerry Pepi (Grinnell R & D), Ulrich Rieger (Total Walther), and Roger Thomas (TTS, Sydney). To Brenda Hoskins for the professional and cheerful manner in which this report was typed.

A special thank you to William Carey at Underwriters Laboratories, and Dan Madrzykowski at NIST for willingly providing vital information.

To Dr Charles Fleischmann for offering his assistance and guidance to a geographically remote student.

To my wife Joasia, for being understanding and supportive to a man who chained himself to a desk every weekend for a year.

Thank you all.

TABLE OF CONTENTS

PAGE

Acknowledgments i
Table of Contents ii
Abstract v
List of Figures and Tables vi
Nomenclature x
Glossary of Terms and Abbreviations xii

CHAPTER

1.0 **Introduction** **1**
1.1 Background 1
1.2 Aims of this Project 2

CHAPTER

2.0 **Literature Review** **3**
2.1 Overview 3
2.2 Residential Sprinkler Systems Utilising Class A Foam Solution 3
2.3 Protection of Vertically Racked Plastic Boxes 4
2.4 Fixed Overhead Compressed Air Foam Systems 14
2.5 Manual Fire Fighting with Class A Foam 16
2.6 Suppression Effectiveness of Class A Foams 22
2.7 Extinguishment of Plastic Fires with Plain Water and Dilute Solutions of AFFF 27

CHAPTER

3.0 **Theory** **29**
3.1 Water As An Extinguishing Agent 29
3.2 Sprinkler Droplet Size and Distribution 30
3.3 Sprinkler Spray Distribution 32
3.4 Sprinkler System Suppression 34
3.5 Sprinkler Suppression Model 38
3.6 Class A Foam Suppression 40
3.7 Foam Expansion Ratio And Its Effect On Suppression 44
3.8 Aspirated Foam Stability 46

CHAPTER

4.0 **Experimental Apparatus** **48**
4.1 Foam Expansion Tests 48
4.2 Foam Distribution Tests 50

TABLE OF CONTENTS

CHAPTER

5.0 Experimental Procedure 52
5.1 Foam Expansion Tests 52
5.2 Foam Distribution Tests 55

CHAPTER

6.0 Results and Observations 56
6.1 Foam Expansion Tests 56
6.2 Foam Distribution Tests 58
6.3 Discussion 60

CHAPTER

7.0 Environmental Considerations 64
7.1 Introduction 64
7.2 Toxicity 65
7.3 Biodegradability 67
7.4 Fish Toxicity 68
7.5 Conclusion - Environmental Implications 70

CHAPTER

8.0 System Hardware and Material Compatibility 75
8.1 Introduction 75
8.2 Bladder Tank Proportioning 75
8.3 Balanced Pump Proportioning 79
8.4 Material Compatibility and Corrosion 81

CHAPTER

9.0 Potential Applications 86
9.1 Introduction 86
9.2 Plastic Commodities 86
9.3 Paper Products and Storage 88
9.4 Limited Water Supply Situations 89
9.5 Warehousing of Stored Rubber Tyres 90

TABLE OF CONTENTS

CHAPTER

10.0 Recommendations and Conclusions 96
10.1 General Conclusions 96
10.2 Future Research 98

REFERENCES 100

Appendix 1: Physical Properties 106
Appendix 2 : Environmental Properties 109

ABSTRACT

Class A foam is often used in the suppression of wildland and structural fires, with manual application methods. This report examines the feasibility of utilising class A foam extinguishing medium in automatic wet pipe sprinkler systems.

Previous researchers report that for certain applications the addition of class A foam solution to a sprinkler system increases suppression effectiveness. Researchers investigating applications with manual fire fighting techniques, using this extinguishing medium, report mixed conclusions.

The integration of class A foam hardware with standard wet pipe sprinkler technology is discussed. Consideration is given to potential corrosion effects and compatibility with sprinkler hardware items. A review of environmental issues revealed that some products are readily biodegradable, while others are not, and that results vary with the test method used.

Tests undertaken to investigate the relationship between the applied sprinkler head pressure and the foam expansion ratio, revealed that only a slight increase in the expansion ratio occurred when the pressure was increased from 50 kPa to 85 kPa. Expansion ratios obtained were similar to those obtained by other researchers using AFFF type foam solution. Foam-water distribution tests indicated that the distribution densities obtained with class A foam sprinkler arrays are within close proximity to the densities obtained using pure water.

It is suggested that future work in this area should be based around the protection of extreme class A hazard type fires.

LIST OF FIGURES AND TABLES

CHAPTER 2 **PAGE**

Figure 2.3-1 Polypropylene Plastic Boxes, Rack Stacked 5
Figure 2.3-2 Test Configuration using an "In Rack" Class A Foam Based Sprinkler System 6
Figure 2.3-3 Test 3 Fire Development 9
Figure 2.3-4 Fire Damage Associated with Test 1 10
Figure 2.3-5 Fire Damage Associated with Test 3 12
Figure 2.3-6 Fire Damage Associated with the Class A Foam Based System 13
Figure 2.5-1 Results of Structural Fire Fighting Room Burn Tests (Time until HRR was 500kW) 20
Figure 2.5-2 Results of Structural Fire Fighting Room burn Tests (Quantity until HRR was 500kW) 21
Figure 2.6-1 Schematic of the Nozzle Arrangement for the Crib Fire Tests 25

CHAPTER 3

Figure 3.3-1 Typical Spray Pattern for a Standard Spray Type Sprinkler 32
Figure 3.3-2 Variation in Mass Flux Density as a Function of Radial Distance 33
Figures 3.3-3a,b,c Effect of Discharge Pressure on Floor Level Spray Patterns 34
Figure 3.3-4 Flow Contours for a Standard Pendant Spray Sprinkler 35
Figure 3.5-1 610mm Wood Crib Heat Release Rates at Varying Densities 40
Figure 3.6-1 Surface Tension Valves for Water and Class A Foam Solution 41
Figure 3.6-2 Surface Contact Angle 42
Figure 3.7-1 Aspirated Foam Formation for a Foam Water Sprinkler 44
Figure 3.7-2 Mesh type Diffuser Aspirating Head 45

CHAPTER 4

Figure 4.1-1 Schematic Representation of the Test Configuration 48
Figure 4.1-2 Foam Slider Collector Board 50
Figure 4.2-1 Foam Distribution Test Array 51

CHAPTER 5

Figure 5.1-1a,b Position of Foam Slider Board 54

LIST OF FIGURES AND TABLES

CHAPTER 6 **PAGE**

Figure 6.1-1 Expansion Ratio as a Function of Pressure 57
Figure 6.1-2 Foam Expansion Tests 58
Figure 6.2-1 Foam Distribution Test Number 1 59
Figure 6.2-2 Foam Distribution Test Number 2 60
Figure 6.3-1 Density Variation for Tests 1 and 2....................62
Figure 6.3-2 Density Variation for Tests Conducted by Factory Mutual with Plan Water....................63

CHAPTER 8

Figure 8.2-1 Typical Schematic of Hardware Arrangement for Class A Sprinkler System, utilising a Bladder Tank 78
Figure 8.3-1 Typical Schematic for Balanced Proportioning with a Pumped Concentrate Supply and In Line Pressure Proportioner....................79

CHAPTER 9

Figure 9.5-1 Tyre Storage Test Configuration - FMRC Test 1 92
Figure 9.5-2 Tyre Storage Test Configuration - FMRC Test 2 92
Figure 9.5-3 Tyre Storage Test Configuration - FMRC Test 3 93

LIST OF FIGURES AND TABLES

CHAPTER 2 **PAGE**

Table 2.3-1 Results of Full Scale Fire Tests with Racked Plastic Boxes 8
Table 2.3-2 Results of Full Scale Fire Tests with Racked Plastic Boxes and Class A Foam 11
Table 2.4-1 Summary of Kim and Dlugogorski's Class A Confined Fire Tests 15
Table 2.5-1 Results of "Salem Tests" 17
Table 2.5-2 University of Wuppertals Room Fire Test Results 18
Table 2.6-1 Size Distribution of Smoke from Fire Suppressant Foam Agents Extinguishment 24
Table 2.7-1 Extinction Time for Common Plastics with Plan Water and 0.2% AFFF Solution 27

CHAPTER 3

Table 3.2-1 Estimated and Measured Valves of Mean Sprinkler Droplet Size 31
Table 3.7-1 Foam Expansion Ratios for Various Discharge Hardware Devices 46

CHAPTER 4

Table 4.1-1 Summary of Equipment used in Foam Expansion Experiments 49

CHAPTER 6

Table 6.1-1 Results of Foam Expansion Tests 56
Table 6.1-2 Results of 25% Drain Tests 57
Table 6.2-1 Foam Distribution Test Number 1 Results 58
Table 6.2-2 Foam Distribution Test Number 2 Results 59

CHAPTER 7

Table 7.5-1 Estimates of the Quantity of Class A Foam Discharged from a Sprinkler System, based in 8 Heads Operating 71
Table 7.5-2 Estimates of the Quantity of Class A Foam Discharged from a Sprinkler System based on Typical Sprinkler System Design Parameters 72
Table 7.5-3 Toxicity Characteristics of Fire Ground Run-Off Water and Class A Foam Solution 73

LIST OF FIGURES AND TABLES

CHAPTER 8 **PAGE**

Table 8.4-1 Uniform Corrosion Rates for Steel and Brass with Fresh Concentrate....82
Table 8.4-2 Uniform Corrosion Rates for Steel and Brass with 1% Foam Solution....83
Table 8.4-3 Typical Materials Exposed to Foam Concentrate in Class A Foam System....84
Table 8.4-4 Typical Materials Exposed to Foam Solution in a Class A Foam Sprinkler System....85

CHAPTER 9

Table 9.5-1 Draft Results of the Class A Type Foam Products Tested on Stacked Tyres....94
Table 9.5-2 NIST Stacked Tyre Fire Test Results - Summary....95

NOMENCLATURE

A = *area* m^2

C = *imperical constant (approximately 3.21)*

C, R_o, R_1 = *Rosin-Rammler coefficients*

d = *droplet diameter*

D = *sprinkler orifice diameter (mm)*

D = *Sprinkler orifice diameter (mm)*

d_m = *mean droplet diameter (mm)*

d_m = *volume mean droplet diameter*

E = *expansion ratio*

$f(d)$ = *droplet size distribution function*

$F(r,t)$ = *bubble size distribution function*

Hc = *crib height (mm)*

K = *proportionality constant (inclusive of* ΔP*)*

m = *meters*

P = *orifice pressure (kg/m.sec.*^{2}*)*

P = *pressure kPa*

ΔP = *pressure difference*

Q = *flow rate (*m^3*/sec)*

Q = *flow rate l/min)*

$\dot{Q}(t_{act})$ = *heat release rate at the time of sprinkler activation (*t_{act}*); Kw*

$\dot{Q}(t-t_{act})$ = *post sprinkler activation heat release rate of the fire, kW*

r = *bubble radius*

r_ℓ = *large bubble radius*

r_s = *small bubble radius*

NOMENCLATURE

U= *Water velocity through the sprinkler orifice (m/sec)*

Vfs = *volume of foam solution*

Va = *volume of air*

$\dot{W}''$ = *spray density (l/min/m²)*

We = *Weber number*

γ = *surface tension*

ρ_w = *water density (1000kg/m³)*

σ = *air-water interface surface tension (0.0073 N/m)*

τ = *time constant (s)*

GLOSSARY OF TERMS & ABBREVIATIONS

Aspirate	To draw in air, nozzle aspirating systems draw air into the nozzle to mix with the agent solution.
Class A Fires	Fires involving ordinary combustible materials (such as wood, cloth, paper, rubber and many plastics).
Class A Foam	Foam intended for use on class A fires, made from hydrocarbon based surfactants.
Class B Fires	Fires involving flammable or combustible gases, liquids, greases and similar materials.
Class B Foam	Foam designed for use on class B fires, made from fluorocarbon-based surfactants.
Compressed Air Foam Systems (CAFS)	A generic term used to describe foam systems consisting of an air compressor (or air source), water pump and foam solution.
Concentration	The percentage of foam concentrate contained in a foam solution.
Drainage Time	The time taken for water to drain out of foam. The 25% drainage time is most commonly used.
Expansion	The ratio of final foam volume to original foam solution volume.
Foam	The aerated solution created by forcing air into, or entraining air in a water solution containing a foam concentrate by means of suitably designed equipment or by cascading it through the air at high velocity.
Foam Concentrate	Foam concentrate is a concentrated liquid foaming agent as received from the manufacturer.
Foam Solution	A homogenous mixture of water and foam concentrate in the proper proportions.
Surfactant	A surface active agent.
Wetting Agent	A chemical that, when added to water, reduces the surface tension of the solution and causes it to spread and penetrate exposed objects more effectively.

ABBREVIATIONS

ABS	Acrylonitrile Butadien Styrene.
AFFF	Aqueous Film-Forming Foam.
AFFF ARC	Aqueous Film-Forming Foam Alcohol Resistant Concentrate.
BOD	Biological Oxygen Demand.
CAFS	Compressed Air Foam System
COD	Chemical Oxygen Demand.
Dv0.5	50% of the total liquid is in drops of smaller diameter than that referenced.
Dv0.9	90% of the total liquid is in drops of smaller diameter than that referenced.
Dv0.99	99% of the total liquid is in drops of smaller diameter than that referenced.
FMRC	Factory Mutual Research Corporation.
NFPA	National Fire Protection Association.
NIST	National Institute of Standards and Technology, U.S. Department of Commerce, Technology Administration.
PAH's	Polycyclic Aromatic Hydrocarbons.
U.L.	Underwriters Laboratories Inc.

CHAPTER 1.0 INTRODUCTION

1.1 Background

Closed head foam water sprinkler systems have long been used for the protection of class B type storage and process risks. Prescriptive standards such as NFPA-16A[1] detail the recommended practice for the design, installation and maintenance of these systems. The use of this technology has the advantage as the required sprinkler density needed to suppress the fire can be reduced.

While prescriptive standards such as NFPA-16A cover the protection of a combination of class A and B type fires, the use of class A type foam as a means of protecting class A fires is not covered.

In 1994 the National Fire Protection Association formulated initial plans to undertake a programme to examine the effectiveness of a class A sprinkler system, based on large scale fire tests. Initial thinking envisaged that such technology could be used in the protection of potential extreme class A fires, as encountered in a high level storage warehouse facility[2]. This project currently remains dormant due to funding constraints[3].

The benefits of applying class A foam to forest fires is well understood. Several researches concluded that in wildland fire fighting activities, the application of class A foam solution is more effective than using pure water. Various manufacturers have claimed that class A foam is approximately five times more effective than pure water[4, 5]. These claims are often made without sound scientific tests being undertaken. A range of hardware and application methods is used in this situation, including foam solution through hose streams, compressed air foam systems (C.A.F.S.), and monsoon buckets. Recent research has resulted in fire service crews utilising class A foam technology to fight structural fires[6].

The application of class A foam technology to a closed head, wet sprinkler system has a number of potential applications. Often products of a class A nature are stored in industrial and warehouse situations, to high levels. In such a case a wet pipe sprinkler system must provide a high water application density.

A typical example of such a risk is rubber goods or products, block stacked vertically. The density required to protect such a product when stacked to a height of 6.3m in accordance with New Zealand Standard for automatic sprinkler systems (NZS 4541:1996), requires an application density of 22.5 l/min/m^2. In such a situation the water demand would be large, ie., typically 7,500 l/min. This demand would require large booster pumps and an up-sized pipework array.

In rural areas often sprinkler systems have a limited water supply available, hence the need to utilise this supply efficiently.

In both of the aforementioned examples it would be advantageous to be able to reduce the application density without reducing the level of fire suppression.

1.2 Aims of this Project

The goals of this research project are as follows;

- To examine the current status of class A foam systems including a review of previous research and fire tests and to examine the findings associated with closely related subjects.
- To undertake a review of the theoretical aspects associated with class A foam sprinkler technology.
- To examine the likely environmental impacts associated with this technology.
- To discus suitable hardware configurations and considerations.
- To undertake a series of tests to evaluate;
  ~how foam expansion ratios are affected by sprinkler head pressure.
  ~ to examine sprinkler distribution patterns associated with class A foam compared to plain water.
- To identify potential applications and make recommendations for further research.

CHAPTER 2.0 LITERATURE REVIEW

2.1 Overview

A literature review was undertaken to establish the results of previous fire tests and research findings. This exercise confirmed that little research has been done in the field of Class A foam water sprinkler systems; hence only a minimum amount of literature has been published. In contrast, a comprehensive number of research papers has been published relating to compressed air foam systems (C.A.F.S.) and structural fire fighting using Class A foam technology. These related topics have been referenced in this report as their findings are of significant interest and closely linked to the subject matter.

2.2 Residential Sprinkler Systems Utilising Class A Foam Solution

In 1995 Underwriters Laboratories Incorporated undertook a series of fire tests for the United States Fire Administration, with the objective of being able to reduce the quantity of water required for residential sprinkler systems protecting mobile homes and rural housing[7].

Fire tests were conducted in the living room of a manufactured home with dimensions 6.6m by 11.3m. A standard UL1626 residential fuel package, consisting of a wood crib and simulated furniture, was used for the fire load. This arrangement was placed in the corner of the room.

Six closed head residential style sprinkles were installed on a CPVC piping network forming a two by three array. Thermocouples were installed at various locations to monitor sprinkler activation temperature, temperature above the wood crib, and to gauge tenability conditions.

Ten fire tests were conducted for a combination of suppression agents based on; pure water, water with 0.3% Class A foam additive, water with antifreeze additive, water with 6% wetting agent.

A fixed quantity of suppression agent (either 50 or 100 U.S. gallons) was applied to the fire and visual observations made as to whether the fire was suppressed or not.

The tests concluded that the pre flashover fires could be suppressed with either 50 U.S. gallons of either 6% wetting agent or 0.3% Class A foam solution.

It was not possible to suppress the fire with 50 gallons of pure water, although suppression was achieved with 100 U.S. gallons of water. Antifreeze solution combinations with a quantity of 50 gallons of solution produced unacceptable results, but with 100 gallons were successful. In all of the successful tests only one sprinkler head operated.

2.3 Protection Of Vertically Racked Plastic Boxes

In March 1996 German based fire equipment manufacturer Total Walther undertook two series of full scale fire tests on high level racked plastic boxes[8, 9]. The objective of the tests was to evaluate the effectiveness of "in-rack" sprinkler systems. The first series of experiments undertook tests using plain water and 3% AFFF foam solution[9]. The second series of tests evaluated the effectiveness of class A foam solution (0.5%)[8].

The fire load consisted of a number of small polypropylene boxes stacked in a racking configuration 9m wide by 10.7m high. The individual plastic boxes were arranged in a double row, within tiers 0.5m apart, as detailed in figures 2.3-1 and 2.3-2.

In-rack sprinkler heads were located in the centre of the rack and spaced 1.45m horizontally with rows of heads located at elevations of 3.7m, 7.2m an 10.7m. In addition to the in-rack sprinklers, 15mm orifice heads were installed at roof level at a height of 14m. Spray type, closed bulb, 10mm fast response sprinkler heads, with a nominal operating temperature of 68^0C and RTI of 50-80 $m^{½}.Sec^{½}$, were installed in the pendant position. Temperatures were recorded at various locations, (refer figure 2.3-2).

Figure 2.3-1: Polypropylene plastic boxes rack stacked[9]. (Note; the yellow triangles indicate the sprinkler positions and the white labels thermocouple locations).

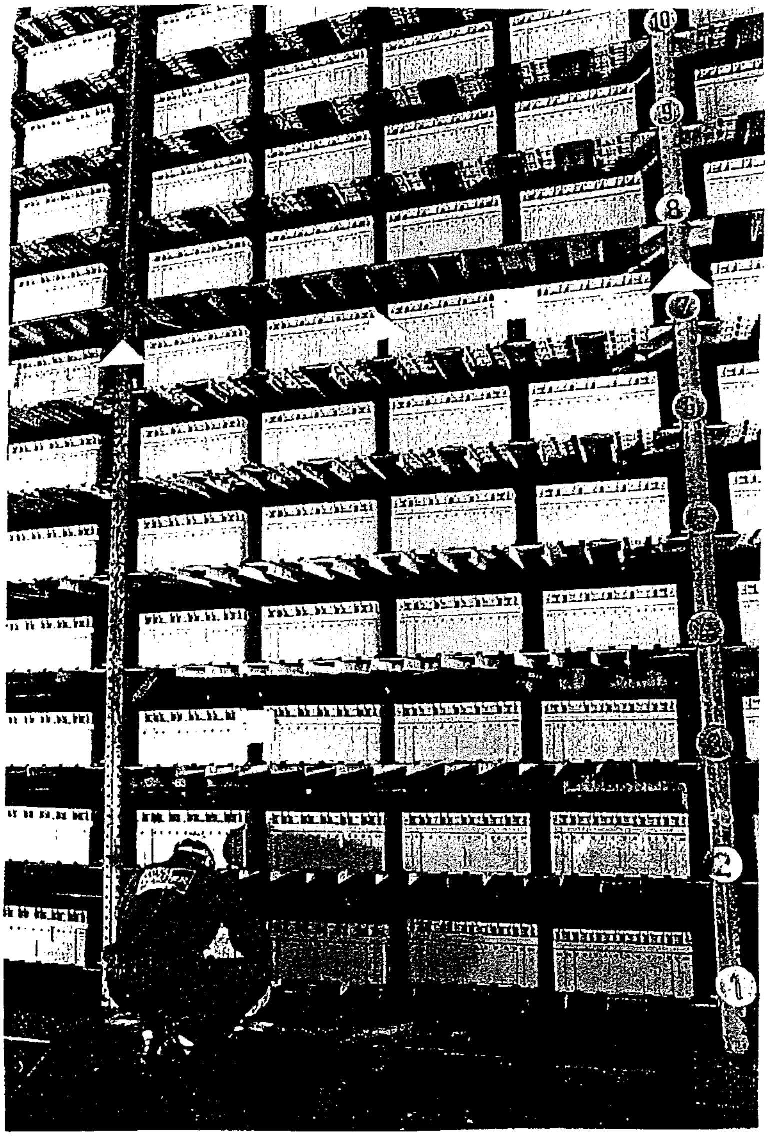
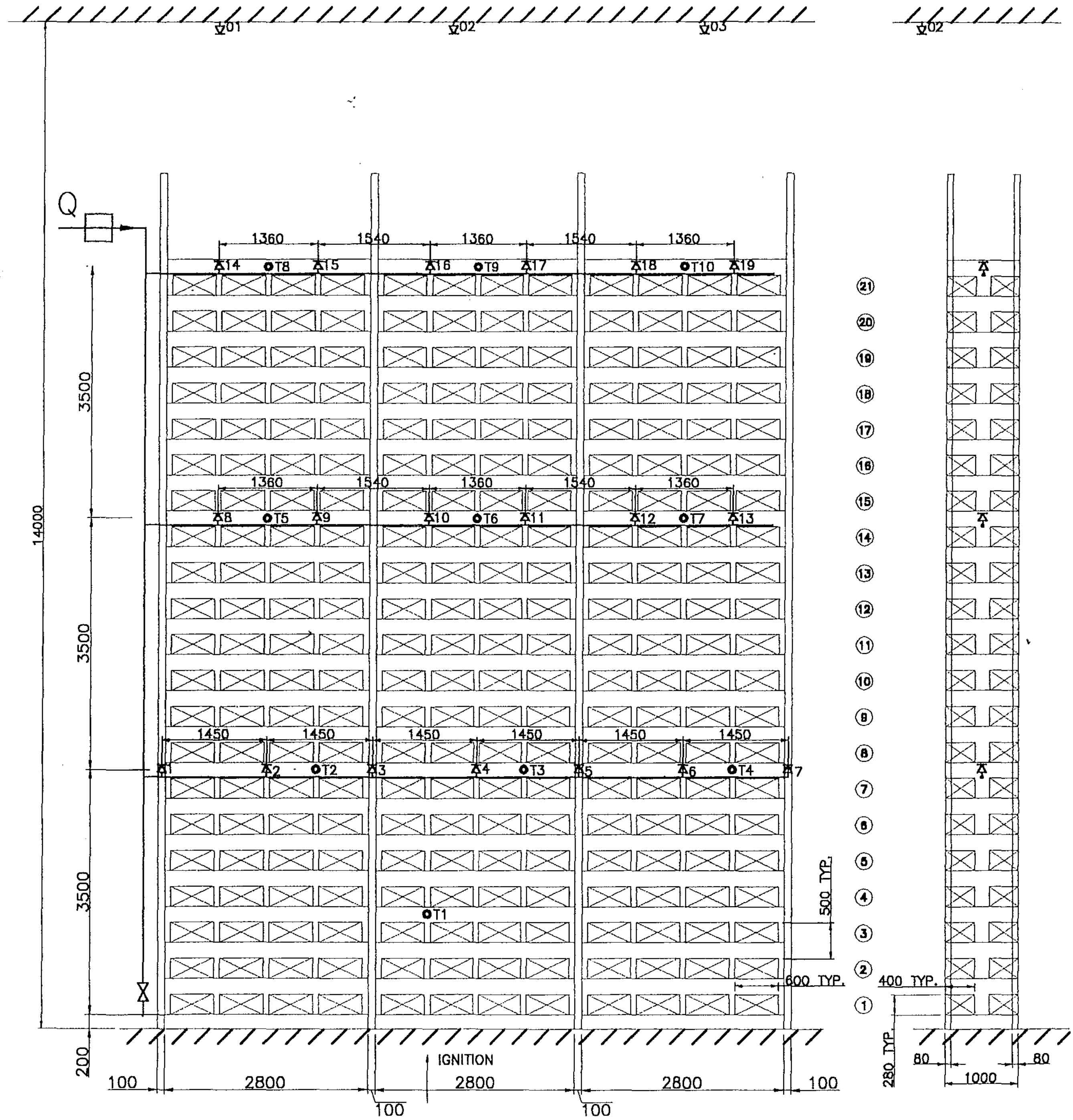


Figure 2.3-2: Test configuration using a "in rack" sprinkler system.[9]



After three sprinklers had operated the flow rate to the heads was regulated to achieve density requirements in accordance with the German sprinkler code for high level rack protection, (BG4.3, extra high hazard, 10 $l/min/m^2$). This typically resulted in the operation of two of the 10mm orifice heads flowing approximately 150 l/min each, at a pressure of 700kPa. The operation of three heads permitted each head to deliver approximately 50 l/min at a pressure of about 100kPa.[9]

In some of the tests a steel "heat collector" device was placed above the sprinkler heads in order to trap the rising heat and increase the rate of response.

Ignition of the plastic boxes was initiated by using a small amount of heptane in a pan. Ignition of the fire load for all tests occurred in the same location, (ie., in the central row at low level as shown in figure 2.3-2). Fire tests that were not controlled by the sprinkler system were extinguished by manual means.

Table 2.3-1 lists a summary of the results of the first series of fire tests.

Table 2.3-1: Results of full scale fire tests with racked plastic boxes (Test Series 1).[9]

Test No.	Foam Used	Sprinkler Heat Collector Used	Rack Sprinklers Actuated		Roof Sprinklers Activated		Quantity of Agent Used M^3	Temp. Max. ^{0}C	Fire Controlled
			No.	Time (Sec)	No.	Time (Sec)			
1	No	No	4 3 6 11 12	218 256 - - -	"3"	>250	4.3	T1 = 820 T2 = 58 T3 - 75 T4 = 40 T6 = 128 T7 = 53	No
2	Yes	No	4 3 5 10/16 11/17 12/18 14/19 15	230 250 - - - - - -	"6"	>300	5.8	T1 = 890 T2 = 80 T3 = 260 T4 = 65 T6 = 180 T7 = 155	Note; Test Stopped Due to Intensity of Fire
3	Yes	Yes	4 3	208 226	-	-	2.7	T1 = 860 T2 = 58 T3 = 55 T4 = 30 T6 = 60 T7 = 36	Yes
4	No	Yes	4 3 5	210 212 634	-	-	7.3	T1 = 818 T2 = 46 T3 =556 T4 = 36 T6 = 80 T7 = 44	Yes
5	No	Yes	4 3	204 237	-	-	9.4	T1 = 820 T2 = 60 T3 = 60 T4 = 34 T6 = 80 T7 = 45	Yes

Figures 2.3-3 shows the developing fire growth for test 3. Figure 2.3-4 shows the fire damage associated with test number 1 (not controlled), while figure 2.3-5 shows resulting damage of test number 3 (controlled).

Figure 2.3-3: Test 3 Fire Development.[9]

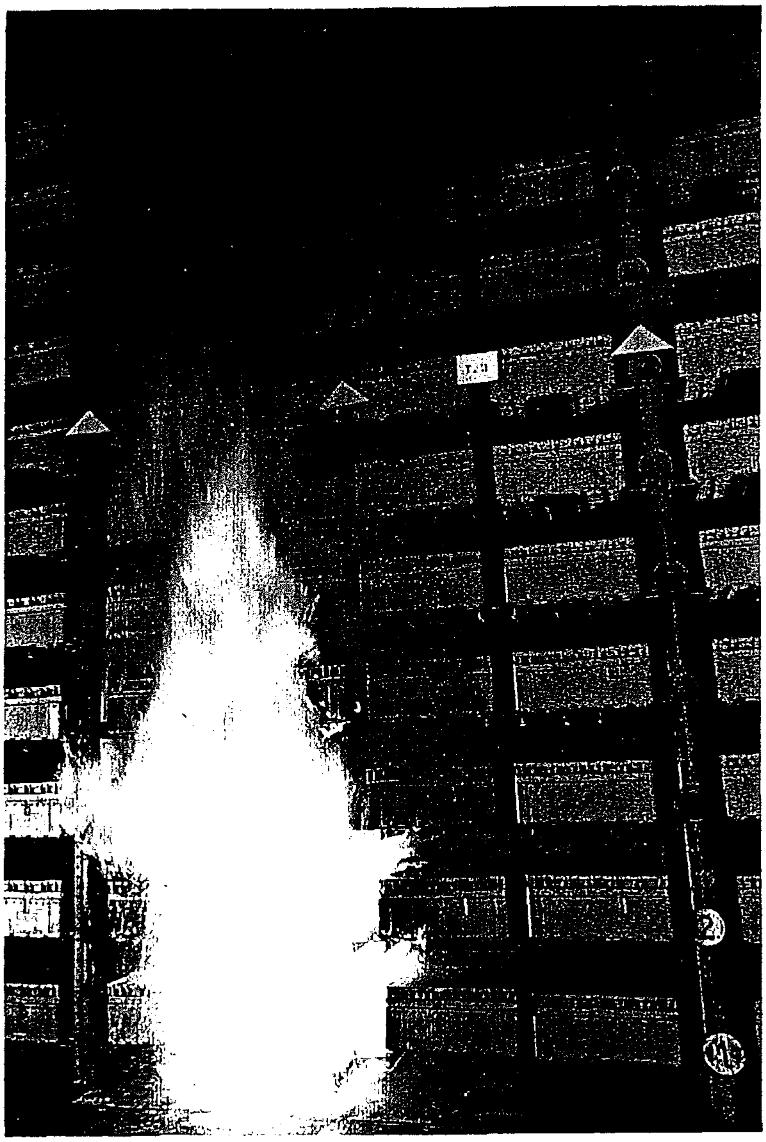


Figure 2.3-4: Fire Damage associated with Test 1 (Not Controlled).[9]

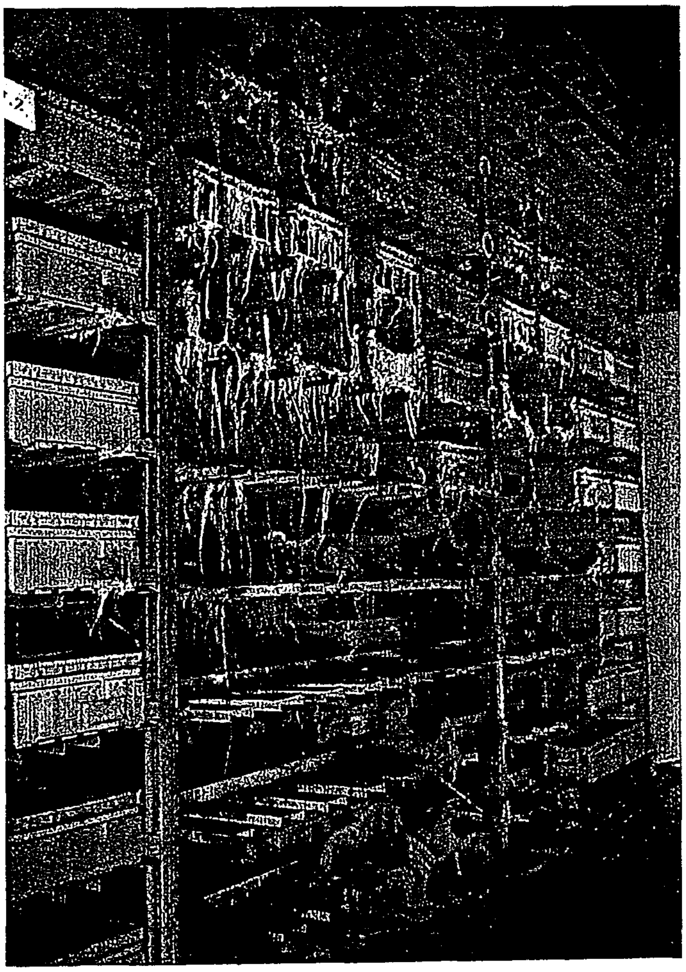


Table 2.3-2: Results of Full Scale Fire Tests with Racked Plastic Boxes and Class A Foam.[8]

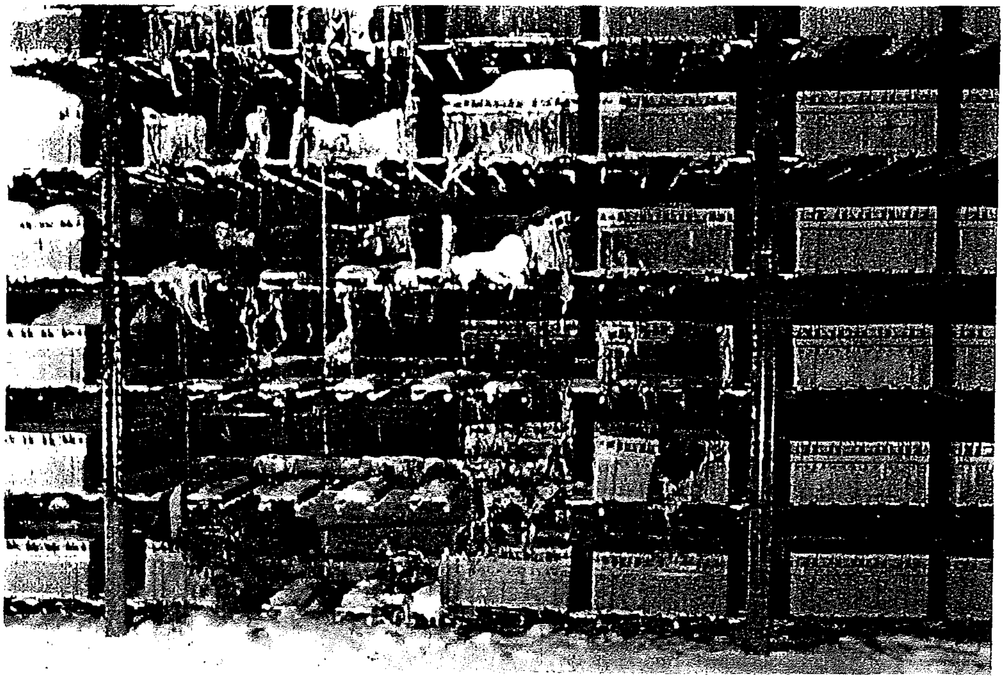
Test No.	Foam Used	Sprinkler Heat Collector Used	Rack Sprinklers Actuated		Roof Sprinklers Activated		Quantity of Agent Used M^3	Temp. Max. ^0C	Fire Controlled
			No.	Time (Sec)	No.	Time (Sec)			
1	Yes (Class A 0.5%)	Yes	4 3 10	230 280 290	-	-	4.7	T1 = 760 T2 = 60 T3 - 50 T4 = 30 T6 = 80 T7 = 30	Yes

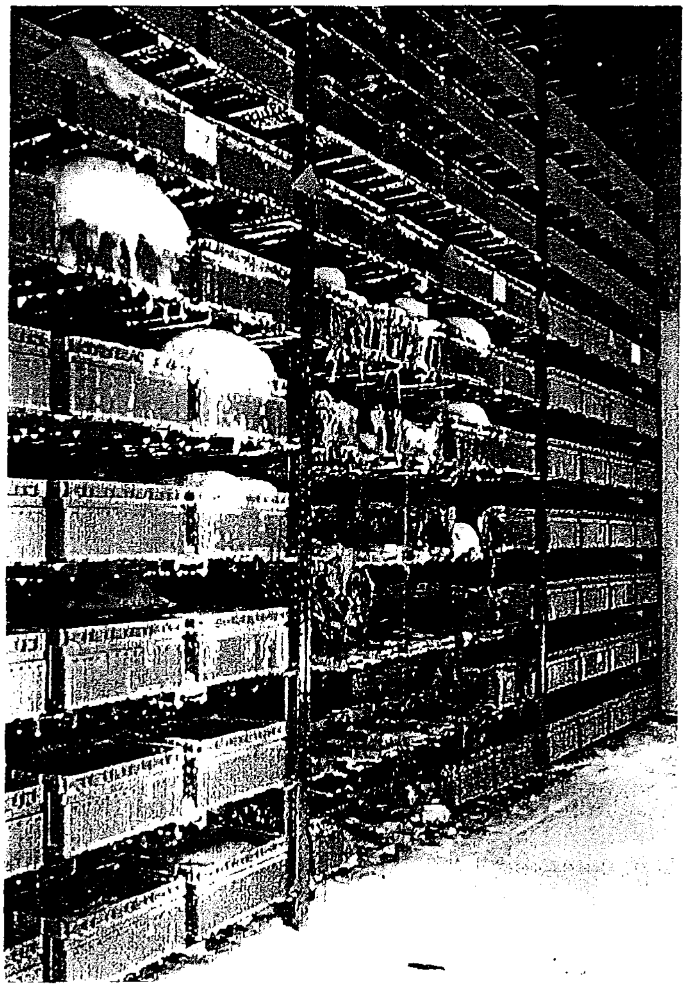
Figure 2.3-5: Fire Damage associated with Test 3 (Controlled).[9]

The authors concluded that with the extinguishing agents and configurations used in tests 3, 4 and 5 the fire load could be controlled.[9]

The second series of tests utilised the same fuel load and configuration. Tests were undertaken with a class A foam solution (Ansul Silv-ex) at a pre-mixed ratio of 0.5%.[8] This addition proved to be successful in controlling the fire. The results of this experiment are detailed in Table 2.3-2.

Figure 2.3-6: Fire Damage associated with the Class A Foam Based System.[8]





The two series of fire tests demonstrate that a fire within the storage array can be controlled by either; plain water, 3% AFFF foam solution or 0.5% class A foam solution. In all these successfully "controlled" cases the array requires; a minimum density of 10 $l/min/m^2$ (as per the German requirements GB4.3), sprinkler head heat collection devices are required and sprinkler spacing shall be as per the test configuration.

The test series has its short comings, as with the exception of tests 4 and 5, individual tests were not repeated in order to reconfirm the results.

The test data indicates that 3% AFFF solution (test 3) was the most effective extinguishing medium. This test used the least amount of agent ($2.7m^3$) and resulted in the least fire damage, (as viewed in the photographs). The 0.5% class A foam appears to be the next most effective agent, where $4.7m^3$ of agent was used as opposed to $7.3m^3$ and $9.4m^3$ for the two "controlled" tests which utilised plain water (tests 4 and 5). The photographs detailing the resulting fire damage reinforce this assumption. The recorded temperatures indicate similar profiles for all the successfully controlled fires.

2.4 Fixed Overhead Compressed Air Foam Systems

Kim and Dlugogorski[10] conducted fire tests using a purpose engineered fixed overhead compressed air foam system. Tests were performed on both Class A and B type fires, in open space, and enclosed compartments. The fire suppression effectiveness of the overhead C.A.F.S. system was compared to that obtained for sprinklers and water mist systems. This report will only examine the comparable results obtained for the compartment fire tests conducted with Class A wood crib fires.

The compartment fire tests were undertaken in an enclosure measuring 6.1m x 6.1m x 3.2m high. The ventilation was achieved through two open windows with dimensions 1.5m by 1.2m located 1.5m above the floor and separated by 0.25m. The door to the enclosure remained closed following the fuel pre burning period.

The rate of heat release for the series of tests was determined by the readings obtained from thermocouples distributed throughout the enclosure in conjunction with the combustion gas concentrations obtained from an overhead oxygen consumption calorimeter.

Wood cribs constructed out of pine, with dimensions 0.6m x 0.6m x 0.6m, were used for the Class A fires. These units were positioned in the center of the compartment 3m below the nozzle array. The cribs were pre burned for a period of two minutes. The heat release rate data confirmed that the cribs did reach the fully developed stage during the pre burn period.

The purpose engineered C.A.F.S. system discharged expanded foam, with an expansion ratio of 1:10 through specially engineered nozzles, with no impingement points. Foam flux density tests found the applied density to range from 8 $l/min/m^2$ immediately underneath a nozzle to 1 $l/min/m^2$ at the spray pattern boundary.

Table 2.4-1 shows a summary of the results of the compartment Class A wood crib fire tests.

Technology	Nozzle Type	Nozzle Quantity	Additive	Fire Reduced	Extinguishment Time (min:s)
Water Mist	Spraying Systems 7G-5	2	None	No	No
Sprinkler	Standard Pendant	2	None	No	No
C.A.F.S.	Special	4	0.3% Class A	Yes	7:16
C.A.F.S.	Special	4	0.3% Class A	Yes	5:56

Table 2.4-1: Summary of Kim and Dlugogorski's Class A Confined Fire Tests[10]

The large cribs clearly provided a challenging deep seated Class A fire. Kim and Dlugogorski concluded that the specially engineered fixed overhead C.A.F.S. system demonstrated a superior suppression performance when compared to standard sprinklers and the water mist systems tested.[10]

The actual amount of water consumed in each test is not published. This is a valuable parameter when comparing the effectiveness of various suppression agents and hardware configurations.

Tests were not undertaken to evaluate how Class A foam solution discharged through a standard or aspirating type sprinkler head performed against the other agents tested. The paper states that the sprinkler droplet size diameter was tested at a pressure of 180 kPa but it is unclear if the actual tests were performed at this pressure.

2.5 Manual Fire Fighting With Class A Foam

In the evaluation of manual fire fighting techniques, a number of researchers have undertaken tests and compared the efficiency and capacity of, plain water Class A foam solution and compressed air form systems. There is considerable variation in the techniques used by the various researches to evaluate the performance of the agents and application methods. Evaluation techniques employed by researchers include; time for suppression, quantity of agent applied, time for a reduction in the heat release rate to a set value, normalised heat release reduction rates, time-temperature reduction relationship or a combination of the aforementioned.

Colletti[11] describes a series of tests that were undertaken as a joint venture between Fire Service Officials and representatives from the fire protection industry. These tests were known as the "Salem tests". Post flashover compartment fires were performed with a fuel package which consisted of wooden pallets and straw. Thermocouples were positioned at the ceiling level and at an elevation of 1.2 meters above the floor. Three agents were evaluated; water, 0.5% Class A foam solution and CAFS aspirated foam solution. The evaluation was based on the time-temperature reduction relationship. The initial fire attack was applied at high level, hence there was little variance in the ceiling thermocouple readings for all three agents. Table 2.5-1 shows the results of the three agents.

Table 2.5-1: Results of the "Salem Tests[11]"

Agent	Time To Reduce From 538^0C to 100^0C	Quantity of Agent
Water	222.9 seconds	287 litres
Foam Solution	102.9 seconds	132 litres
Compressed Air Foam	38.5 seconds	50 litres

Colletti also claimed that there was an improvement in fire fighting visibility with the application of the compressed air foam. This opinion was previously stated by the same author in a previous publication[12].

The UK based Home Office Fire Experimental Unit evaluated various class A water alternatives, which were applied to a fully developed unrestricted fire, consisting of a 2 x 2 x 14 high array of wooden pallets[13]. Two series of tests were conducted in 1995 and 1996 respectively. The fire tests were performed under a large exhaust hood. Temperature and radiative flux readings were recorded.

The effectiveness of the water additives was evaluated by calculating the area under the fire, time-temperature curve. In total, thirteen class A additives were evaluated for the purposes of structural fire fighting. The application of the agent to the fire was made with a 50 l/min high pressure hose reel with the nozzle set to spray mode. The report concluded that none of the additives tested produced significant advantage to fire fighting and further investigation could not be justified[14].

Underwriters Laboratories undertook a series of tests for the USDA Forest Service[15]. The primary purpose of these tests was to collate test data, relative to determining a suitable method to evaluate the performance of class A foam based fire fighting methods. These tests were purely quantitative. Due to the range of flow rates, application pressures and crib sizes, it is difficult to draw conclusions as to how class A solution, aspirated class A solution and plain water compared.

Researchers at the University of Wuppertal in Germany have also investigated the possible use of Class A foam for fire fighting purposes[16]. Compartment fire tests were undertaken in a room with dimensions 4.75 x 3.3 x 2.62 meters. A fixed ventilation area was achieved through an open door. The fire load consisted of a 2 x 5 high array of wooden pallets. Recordings were made of; the time for extinguishment, quantity of agent and room and crib temperatures.

Application was achieved with a 25mm smooth bore non-aspirating nozzle. A summary of the results, which are of interest to this project, are shown in Table 2.5-2 below.

Table 2.5-2: University of Wuppertals Room Fire Test Results[16]

Extinguishing Agent	Quantity of Agent Used (Litres)	Time to Extinguishment (min:sec)
Water 1	107	5:30
Water 2	85	6:45
Class-A-foam-1	59	3:00
Class-A-foam-2	55	3:30
Class-A-foam-3	84	3:45

The paper concluded that there was an advantage to using 0.5% class A solution as an extinguishing agent, compared to water. Like Colletti, the author claimed that there was an improvement in the fire fighting visibility, with the application of class A foam, compared with that experienced with plain water[11, 12].

Gravestock[17] has also undertaken studies in this area. This work was carried out on shielded, post flashover fires. The study examined the effectiveness of water mist, water mist with class A foam solution and compressed air foam systems. The evaluation of the effectiveness of the various agents was achieved by comparing the normalised heat release reduction rates obtained by using oxygen calorimetry techniques. The fire load consisted of three kiln dried cribs with dimensions 600 x 600 x 750 mm, which were separated by a medium density fibreboard partition within the compartment.

The research concluded that there was no significant difference found in suppression performance with the three agents[17]. Again, like previously mentioned, researchers findings, observations revealed that there was an increase in visibility when the CAFS agent was applied, compared to the other agents.

The National Fire Protection Research Foundation conducted two comprehensive series of tests into this subject[18]. These tests consisted of a post flashover compartment fire, which was lined with plywood and contained a mock furniture standard UL 1626 residential sprinkler fuel package. Fire ventilation was achieved through a centrally located window with dimensions 1.5 x 1.2 m. Evaluation was undertaken with, plain water, class A foam and compressed air foam.

The measurement of performance was taken as the time it took the heat release rate to reduce to 500 kW, and the amount of agent used. The report concludes that the results from the second series of tests indicate that, "the use of class A foam solutions generally reduced the amount of heat released from the fire and damage to the combustibles as compared to plain water." [18] Figures 2.5-1 and 2.5-2 show the results of the series II fire tests, detailing the time of agent application until a heat release rate was reduced to 500kW.

The references mentioned above give mixed conclusions as to the effectiveness in class A foam solution and aspirated foam solution when compared to plain water.

Due to the variations in the, evaluation techniques, fuel loads, application rates and compartment configurations, it is not possible to compare the results of the above mentioned references. With the exception of the Home Office Report[13], all of the researchers recommend that further testing be undertaken in this area.

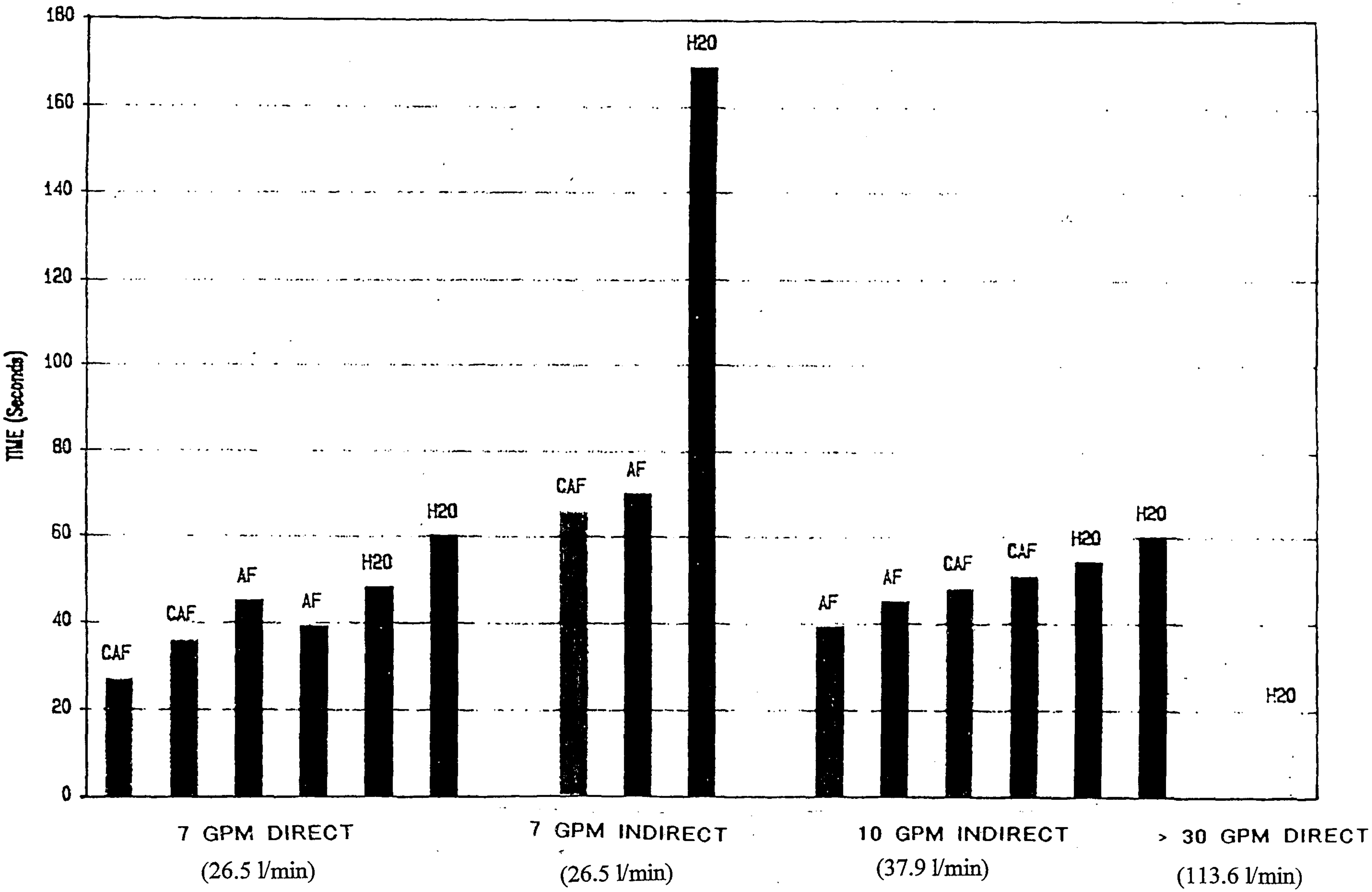


Figure 2.5-1: Results of Structural Fire Fighting - Room Burn Tests Phase II, Time of Agent Application until RHR was reduced to 500kW.[18]

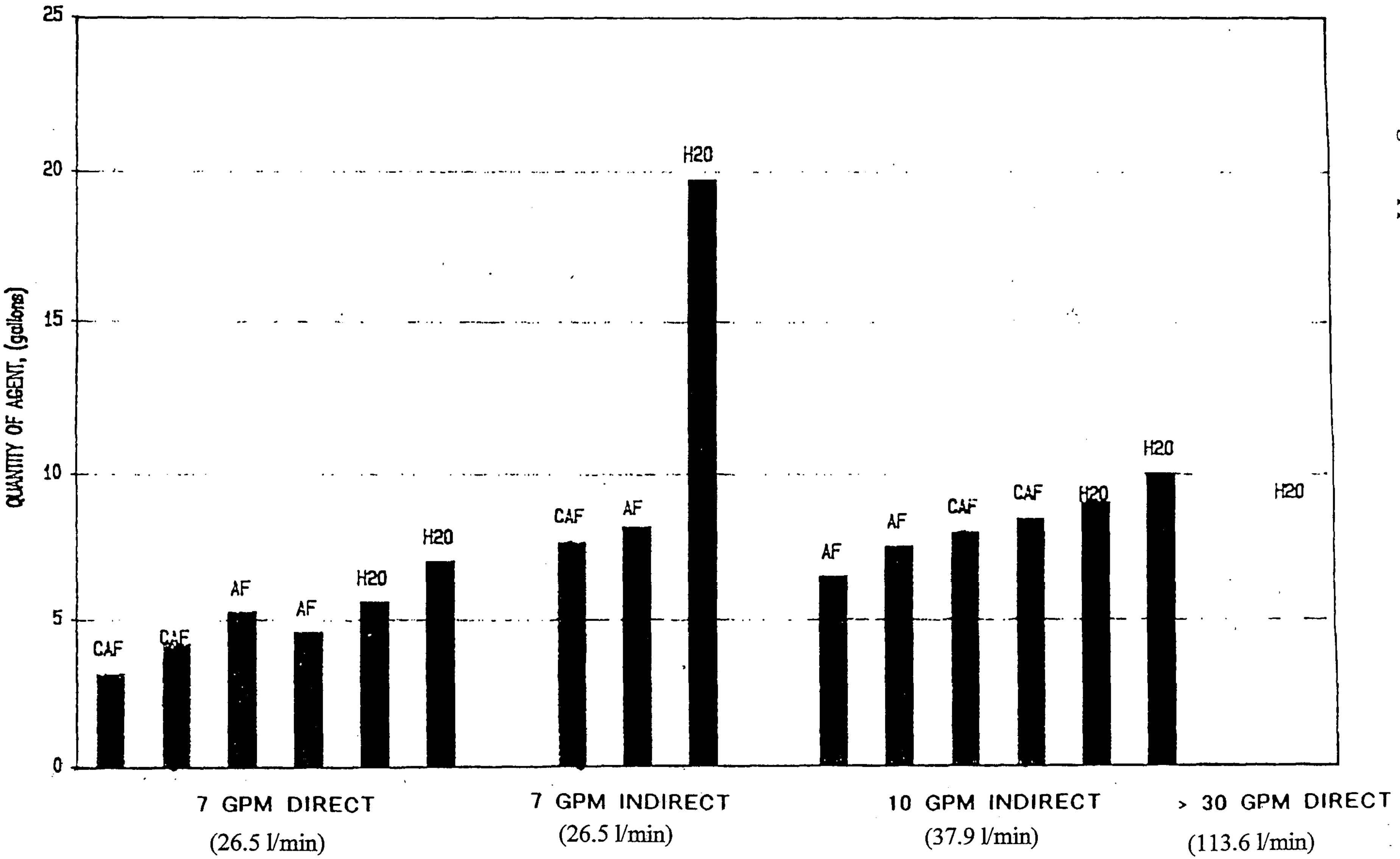


Figure 2.5-2: Results of Structural Fire Fighting - Room Burn Tests Phase II, Quantity of Agent Applied until RHR was reduced to 500kW.[18]

2.6 Suppression Effectiveness of Class A Foams

The United States Fire Administration recognised that no evaluation protocol or standard test methods exist to determine the effectiveness and performance capabilities of class A foams.[19] This made it difficult for the users of class A products, such as rural fire fighting organisations, to relate the performance of a particular agent to that of plain water or to compare various foam agents.

The National Institute of Standards and Technology (NIST) was commissioned in order to undertake tests and develop a suitable evaluation programme. The goals of the report were categorised into four individual tasks as follows;[19]

- Conduct a workshop with interested groups.
- Collate existing information on products.
- Develop methods to assess biodegradability, environmental, toxicity and physical properties.
- Develop methods to assess and demonstrate fire fighting effectiveness.

Section 3.6 of this report references the findings of this study in relation to the foam agents fire fighting and physical properties. The biodegradability, toxicity and environmental factors are discussed in Section 7.0.

The NIST evaluation only tested four agents. The agents selected were deemed to be a typical representation of agents that complied with U.S. Forest Service Specification 5100. The NIST report does not reference the specific foam agent manufacturer or product name.[19]

Exposure protection properties were evaluated by conducting both mass retention and ignition-inhibition experiments.[20] These tests were conducted with water, foam solution and compressed air foam (CAFS). The results of the CAFS tests are not discussed in this report as they are outside the scope of this study.

The mass retention tests were conducted on typical residential external building materials, ie., unstained plywood, stained plywood and a vinyl cladding. Tests were undertaken on vertical panels with dimensions 1.22m x 2.44m x 13mm.

The effectiveness of the foam solution was measured by determining the ratio of the average mass of agent on the building material at time *t*, to the average mass of water on the panel at time *t*, as derived by the specific water mass retention tests. The results showed that all solutions tested had a similar performance. Foam solution was approximately four times more effective on stained panels, and approximately two times more effective on unstained panels. The foam solution was not as effective on vinyl panels as pure water. This is explained by the solution having a lower surface tension, hence it is likely to run off a non-porous material at a higher rate, compared to pure water.[20]

The "ignition-inhibition" experiments showed that both water and foam solution increased the time to ignition by approximately 40%, with unstained samples and between 16% to 35% for stained samples.[20] There was found to be little to no advantage in using class A foam solution over pure water. The author recommends further research in this area in order to quantify the results.

NIST conducted tests to evaluate the smoke characterisation of crib fires fought with class A foam and water.[21] Two series of tests were undertaken. In the first series, wooden cribs constructed out of "southern pine", were utilised and tests were performed to measure the levels of polycyclic aromatic hydrocarbons (PAH's). PAH analysis determines the ratio of elemental to organic carbon. The second series of tests evaluated the physical and chemical properties of the smoke by determining the concentrations of; carbon monoxide, carbon dioxide, nitrogen oxides, hydrogen chloride and hydrogen cyanide. These tests were conducted with wooden cribs, with plastic sticks (acrylonitrile butadien styrene and polyvinyl chloride), replacing some of the wooden sticks within the array. The second series of tests also analysed the mass concentration and size distribution of the soot particles present in the smoke.

The first series of tests revealed that the fires extinguished with water only showed a high level of the range of polycyclic aromatic hydrocarbons (PAH's) present. In contrast, when foam solution or expanded foam (CAF's) was applied to the wooden crib fires, the formation of PAH's with high molecular weights were suppressed. The author comments that this could be due to the better coating or penetrating properties associated with the foam based agents.[21]

In the second series of tests the application of class A foam solution or CAF's was found to be no more effective than plain water at suppressing the concentration levels of carbon dioxide, carbon monoxide, nitrogen oxides, hydrogen cyanide and hydrogen chloride. The analysis revealed similar trends for the rate of heat release, smoke mass concentration and oxygen concentration, regardless of the extinguishing agent applied.[21]

The second series of tests revealed that the application of foam based solution did appear to effect the size distribution of the smoke particulates. Smaller mean diameter particles were generated as a result of being exposed to class A foam extinguishment agents. The author commented that this effect may present an increase in health hazards to fire fighting crews, as the smaller particles have the potential to penetrate further into the lungs.[21]

Table 2.6-1: Size Distribution of Smoke from Fire Suppressant Foam Agents Extinguishment.[21]

	AERODYNAMIC MASS MEAN DIAMETER, μm		
	Configuration 1	2	3
Pre-extinguishment	1.6	1.6	1.6
Post-extinguishment			
Water	1.4	1.8	1.0
Agent A	0.9	1.2	-
Agent A (repeat)	1.0	-	-
Agent B	1.3	0.8	0.8
Agent C	1.2	0.6	0.6
Agent C (repeat)	-	-	0.8
Agent D	-	1.0	0.7

Notes:

Configuration 1 - 2 nozzles / 5.04 l/min / 275kPa

Configuration 2 - 4 nozzles / 7.95 l/min / 179kPa

Configuration 3 - 4 nozzles / 6.2 l/min / 96kPa

(Refer to figure 2.6-1 for details of nozzle configuration).

The same pre-extinguishing samples are reported for all three extinguishing configurations.

Fire fighting crews have often commented on the amount of "white smoke" associated with fighting a fire with class A foam based extinguishing agents. The smoke characterisation study explained this phenomenon as being caused by the foam agents, possibly promoting the formation of clouds by increased water content of the gases, and providing additional condensation nuclei.[21]

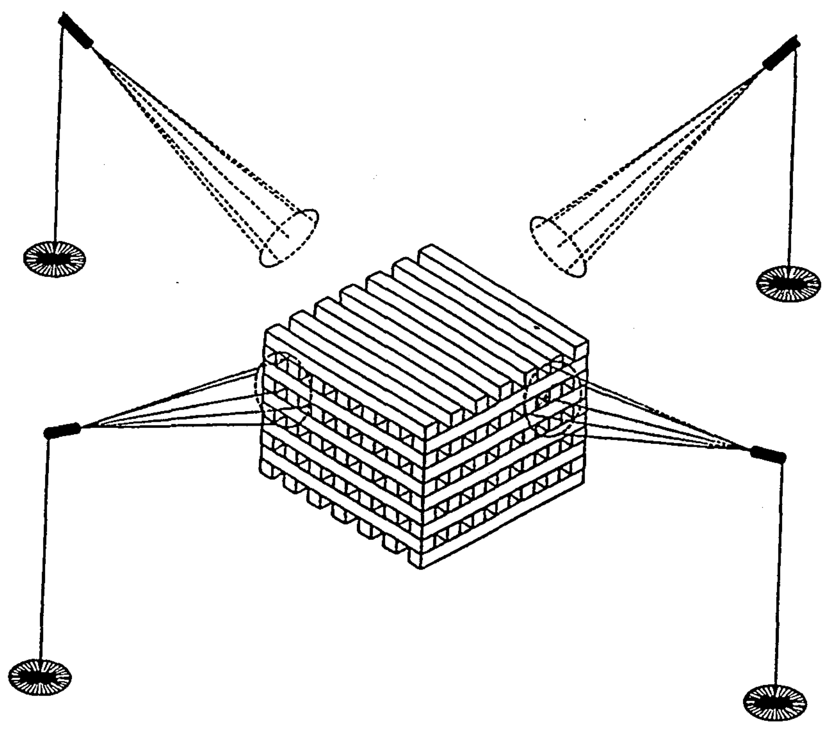
The reduced surface tension of the foam solution leads to more finer droplets with reduced mean diameter, hence the overall surface area of the extinguishing agent is increased which translates to increased evaporation.

Fire suppression experiments were performed as part of the NIST evaluation on crib fires and tyre fires.[22] The results of the tyre fires are discussed in Chapter 9.

The cribs that were tested were constructed out of a combination of southern pine, ABS and PVC sticks, as described in the smoke evaluation tests described above. The cribs consisted of 10 layers of sticks with dimensions (558mm x 38mm x 38mm). The overall mass of the cribs varied between 29-34kg. The PVC sticks constituted 3.2kg of the total mass and the ABS sticks 2.6kg.

The extinguishing agents were applied to the cribs by either two or four foam nozzles. Figure 2.6-1 outlines the crib fire test apparatus.

Figure 2.6-1: Schematic of the Nozzle Arrangement for the Crib Fire Tests.[22]



Heat release rates were derived for each crib fire situation by using a collection hood and furniture calorimeter. The heat release curves showed there to be very little difference in the rate of heat reduction, when comparing the application of water and class A foam extinguishing agents.[22]

2.7 Extinguishment of Plastic Fires with Plain Water and Dilute AFFF Solutions

Commonly used plastics are generally categorised as ordinary combustible Class A materials. Takahashi[23] compared the effectiveness of plain water and dilute solutions of AFFF and ARC type foam concentrates, in extinguishing fires fueled by various commonly used plastics.

Although the examination of Class B type foam concentrates are outside the scope of this study, Takahashi's findings are worth considering. Bench scale tests were performed. Solid plastic fuels were arranged into a netted steel frame in order to support the individual lengths. Typically solid plastic rods with 15 mm diameter and 330 mm long were situated within the frame in a 6 wide x 5 high array, and spaced 35 mm centre to centre apart. Ignition was achieved using a gas burner. A spray type nozzle was centrally located at a height of 900 mm above the top of the array.

The report concluded that the dilute solutions of AFFF and AFFF ARC type foam concentrates were superior in extinguishing plastic fuel fires, when compared to plain water. Table 2.7-1 below lists some of the results.

Table 2.7-1: Extinction Time for Common Plastics with Plain Water and 0.2% AFFF Solution[23]

Plastic	Extinction Time (min:sec) Plain Water	Extinction Time (min:sec) 0.2% AFFF Solution
Polyurethane	0:06	0:08
Polycarbonate	0:14	0:06
Phenolformaldehyde	0:16	0:08
Polymethylmethacrylate	0:18	0:11
Polyoxymethylene	0:45	0:50
Polyethylene	2:00	0:40
Acrylonitrile-butadiene-sylene	2:40	0:20
Polypropylene	No Extinction	2:25

(Note - the application density was 0.38 kg/m^2 per second)

Takahashi also examined the relationship between AFFF foam solution concentration and extinction time. It was found that the extinction time was reduced as the concentration was increased, but become constant beyond a certain concentration saturation level. This actual concentration saturation level varied with the species of plastic. At concentration levels below the saturation point it was concluded that concentration level - extinction time curves closely followed the surface tension - concentration relationship.[23]

CHAPTER 3.0 THEORY

3.1 Water As An Extinguishing Agent

Water is widely used as an extinguishing agent. This can be contributed to a number of factors such as, plentiful supply, low cost, favourable non-toxic properties, chemical stability and good fire suppression capabilities.

Water controls and extinguishes fires by a number of, or combination of mechanisms, depending on the method of application. Suppression mechanisms include; cooling, oxygen depletion, emulsification and dilution. The most dominant mechanism for suppression of Class A solid fuel fires, with manual hose streams or sprinkler systems, is cooling.[24]

The high latent heat of vaporisation (2260 kJ/kg) of water makes it an excellent cooling agent.[24] Water cools the fuel surface and reduces the rate of pyrolysis of the fuel. The application of water to a burning fuel initiates heat transfer from the fire to the water. Fire control is established when the rate of heat absorption to the water equals the net rate of heat release of the fire. Suppression and water extinguishment are achieved when the rate of heat absorption of the water exceeds the rate of heat release.[24]

The method of application, and type of delivery hardware, has an effect on the rate of heat absorption by the water. Ideally, in order to maximise the amount of heat absorption, all of the applied water should be converted into steam. Fire tests have revealed there is an optimum droplet size (ie., 0.3-1.0mm) that should be applied to the fire.[24] The smaller the droplet size the greater the surface area, hence there is increased cooling capacity as the rate of heat absorption is increased with the increased surface area. Limitations on droplet size exist as the individual droplets must have sufficient mass and momentum to overcome the upward fire plume velocity effects, and other gaseous currents which maybe present.[24]

3.2 *Sprinkler Droplet Size & Distribution*

Dundas[25] undertook a series of experiments in order to find a relationship between the sprinkler droplet size, head pressure and orifice diameter. Dundas' findings can be written in terms of the Weber number, *We*;

$$d_m = \frac{CD}{We^{1/3}} \quad \text{Expression 3.2-1}$$

Where d_m - *mean droplet diameter (mm)*
D - *sprinkler orifice diameter (mm)*
C - *imperical constant (approximately 3.21)*
We - *Weber number*

$$We = \frac{\rho_w U^2 D}{\sigma} \quad \text{Expression 3.2-2}$$

With ρ_w - *water density (1000kg/m³)*
σ - *air-water interface surface tension (0.0073 N/m)*
D - *Sprinkler orifice diameter (mm)*
U - *Water velocity through the sprinkler orifice (m/sec)*

Since the flow through a sprinkler is given by,

$$Q = \frac{U \pi D^2}{4} \quad \text{Expression 3.2-3}$$

Where Q - *flow rate (m^3/sec)*

and the dynamic pressure head term is,

$$P = \rho_w U^2 \quad \text{Expression 3.2-4}$$

Where P = *orifice pressure (kg/m.sec.²)*

Combining expressions 3.2-2 and 3.2-3 gives,

$$We = \frac{16 \rho_w Q^2}{\pi^2 Q D^3} \quad \text{Expression 3.2-5}$$

Combining expressions 3.2-2 and 3.2-4 gives,

$$We = \frac{PD}{\sigma} \quad \text{Expression 3.2-6}$$

Combining expressions 3.2-1, 3.2-5 and 3.2-6 it can be shown that,

$$d_m \propto \frac{D^{2/3}}{P^{1/3}} \propto \frac{D^2}{Q^{2/3}} \quad \text{Expression 3.2-7}$$

Expression 3.2-7 states that the mean droplet diameter is inversely proportional to the 1/3 power of the water pressure and directly proportional to the 2/3 power of the sprinkler orifice diameter.

Experimental studies performed by Chow and Shek[26] confirm that the estimated valves of the mean droplet sizes using Dundas' expression were in good agreement with the actual measured valves. Chow and Shek's experiments were undertaken with both conventional type and spray type 15mm commercial sprinklers. The spray drops were examined by photographing a "slice" of the distribution pattern. Chow and Shek's results are summarised in table 3.2-1 below.

P (bar)	*U (m/sec)*	*We*	*Estimated d_m (mm*	*Measured d_m (mm*
0.3	6.14	6197	2.095	2.0
0.6	8.60	12148	1.677	1.5
1.0	11.55	21912	1.377	1.5

Table 3.2-1: Estimated and measured valves of mean sprinkler droplet size d_m[26]

Prahl and Wendt's[27] experimental studies of an axisymmetric sprinkler head confirmed that the droplet size distribution around the mean droplet diameter is in agreement with a Rosin-Rammler distribution curve as proposed by Sellens and Brzewstowski for a spray type sprinkler head.

The droplet size distribution function f(d) is of the Rosin-Rammler form;

$f(d) = R_0(d/d_m)^{c-4}\exp(-R_1(d/d_m)^c)$ *Expression 3.2-8*

Where,	$f(d)$	-	*droplet size distribution function*
	C,R_0,R_1	-	*Rosin-Rammler coefficients*
	d	-	*droplet diameter*
	d_m	-	*volume mean droplet diameter*

Prahl and Wendt found that with Rosin-Rammler coefficients of C=5.0, R_0 = 0.6627 and R_1 = 0.2651 the distribution placed 98% of the droplets sampled with their experimental work to have diameters between 0.2mm and 3.2mm[27].

Kumar et al[28] concluded that the droplet diameter distribution of a commercial style conventional sprinkler head can be seen as having a log-normal distribution.

3.3 Sprinkler Spray Distribution

Conventional or old style sprinkler heads have a deflector which is designed to distribute a certain percentage of its water upwards in order to cool the roof or ceiling structure. Spray style sprinklers distribute water in an umbrella hemispherical pattern, where all of the spray is directed downwards.[29] Figure 3.3-1 shows a typical distribution pattern for a standard spray sprinkler.

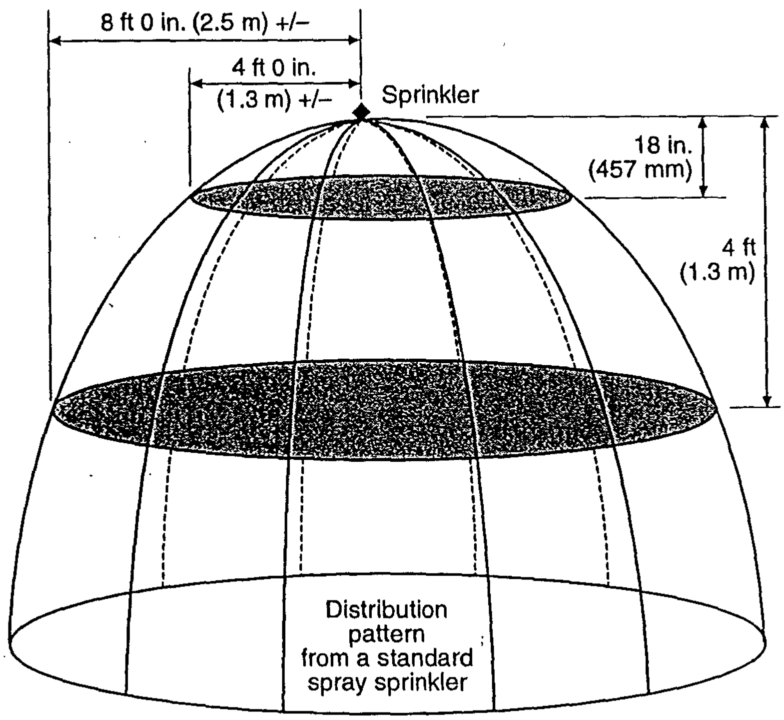


Figure 3.3-1: Typical spray pattern for a standard spray type sprinkler installed in the pendant position.[29]

The mass flux density of a sprinkler is a measure of an individual sprinklers radial water flux distribution.[26] Experimental work has demonstrated that the mass flux density for a standard spray type sprinkler head will initially decrease to a minimum valve, then increase to a maximum valve at a radial distance of approximately 1.6m. Beyond this distance the mass flux density diminishes to zero.[26] This pattern is graphically represented in Figure 3.3-2.

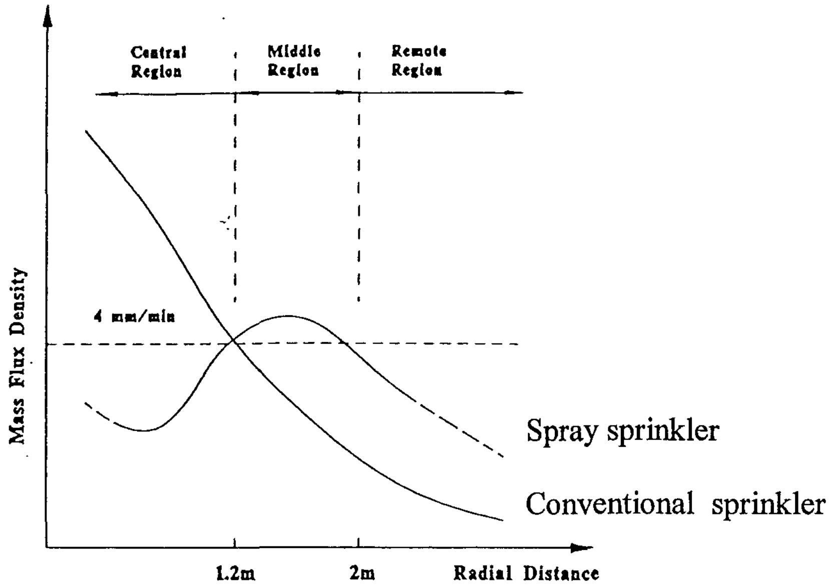


Figure 3.3-2: Variation in mass flux density as a function of radial distance from a sprinkler.[26]

The spray distribution pattern for sprinklers with the same geometry and orifice size will depend on the application pressure. The diameter of the circular coverage will increase with increasing pressure, up to a limit, at which point it reduces and forms and elliptically shaped pattern.[30] Figures 3.3-3a, b, c, show the floor level spray patterns for a half inch nominal orifice sprinkler with different applied pressures.

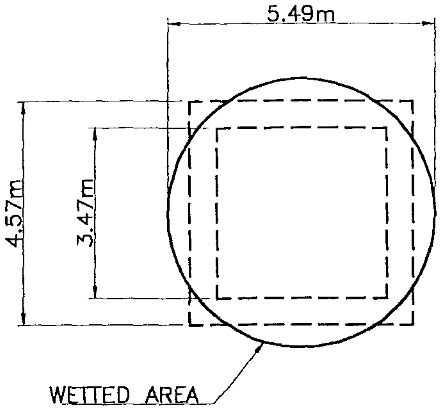


Figure 3.3-3(a) P = 48kPa, Q = 58 l/min
A = 2.32m² $\dot{w}$ = 2.44 l/min

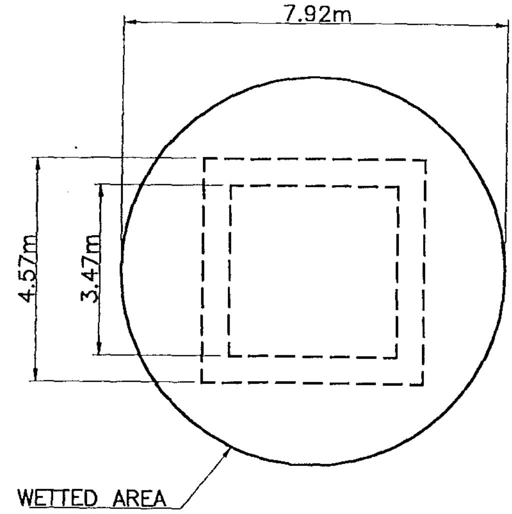
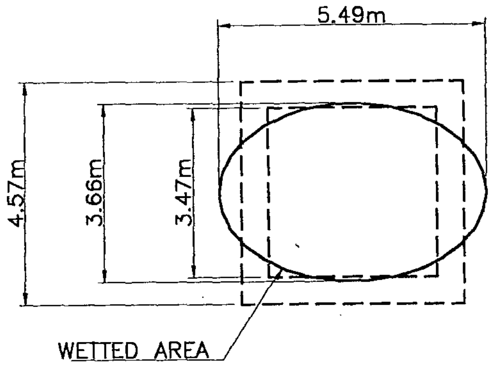


Figure 3.3-3(b) P = 483 kPa, Q = 182 l/min
A = 49m² $\dot{w}$ = 3.75 l/min/m²

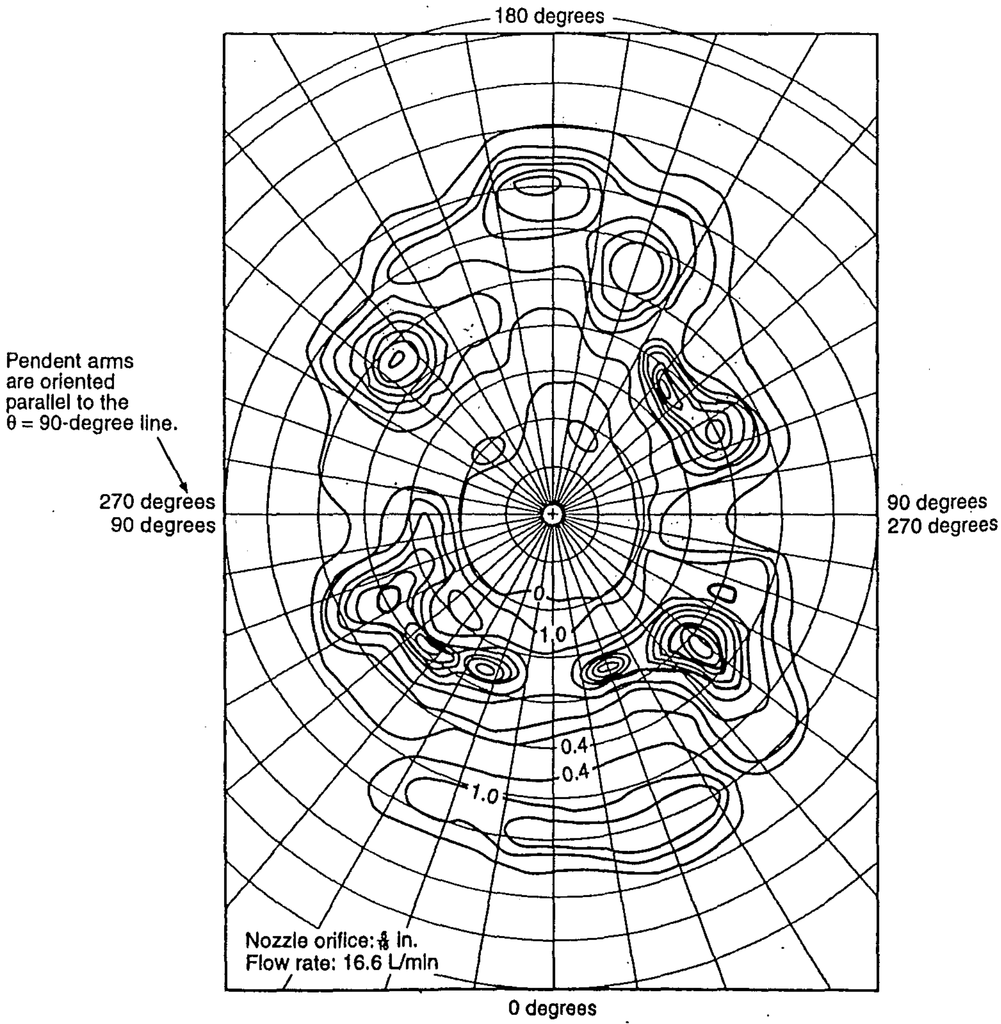


Figures 3.3-3a, b, c: Effect of discharge pressure on floor level spray patterns.[30]

Figure 3.3-3(c) P = 1206 kPa, Q = 287 l/min
A = 15.79m², A = 49m² $\dot{w}$ = 18,35 l/min/m

Due to obstructions caused by the arms of the sprinkler frame and the serrated edges of the deflector, the spray pattern will not be axisymmetrical. Figure 3.3-4 shows the flow distribution pattern for a standard spray type pendant sprinkler head. High densities occur in areas where the flow contour lines are close together.

Figure 3.3-4: Flow contours for a standard pendant spray sprinkler.[27,31]



Prescriptive sprinkler standards require that a minimum discharge design density be achieved by a group of sprinklers. The required design density and assumed area of operation will depend on the potential fire load and the specific requirements of the prescriptive code. Independent sprinkler approvals are based around this concept of achieving an average density with a group of sprinklers. Underwriters Laboratories standard UL199 details two such tests; a 10 pan rotating table test and a fixed 16 pan test.[32]

3.4 Sprinkler System Suppression

Sprinkler suppression and control is based on pre-flash-over activation. Sprinklers[33] can be activated by either convective heat transfer or by radiation.

Convective heat transfer is the most dominant mode for the activation of sprinklers. This occurs as a result of the rising fire plume interacting with the ceiling. The plume is directed horizontally across the ceiling, forming a ceiling jet of hot gases. The immersion of the sprinkler head in the convective hot gas layer causes the detection element of the sprinkler to operate.[30]

Sprinkler heads can also be operated as a result of radiative heat transfer.[33] This situation can occur in the operation of an intermediate level sprinkler. If the sprinkler head is directly engulfed by the rising fire plume it will be activated as a result of convective heat transfer. In the case where the sprinkler head is not directly in the stream of the plume the radiation emitted may be sufficient to activate the sprinkler.[33] The activation response time of the sprinkler depends on a number of factors such as; operating temperature, response time index (RTI), height, geometry and thermal capacity of the ceiling, rate of fire growth and convective heat output, vertical distance between the sprinkler and the ceiling, horizontal distance between the sprinkler and the fire, and the presence of any air movement.[33] A detailed analysis of the aforementioned factors associated with detection and activation response is outside the scope of this project.

The activation of the sprinkler head allows a stream of water to be directed at the impinging deflector. The water leaves the deflector forming an umbrella shaped sheet. At some radial distance from the sprinkler, atomisation of the sprinkler spray occurs.[28] It has been reported that a standard sprinkler will produce in the order of 10^8 water droplets at any one time.[28] The umbrella or hemispherical shaped discharge pattern, consisting of a range of droplet sizes, is distributed to the immediate area.

The droplet surface area can be expressed in terms of the total flow rate and the mean droplet diameter;[30]

$$A_s \quad \propto Q \setminus d_m \quad \textit{Expression 3.4-1}$$

Combining expressions 3.2-7 and 3.4-1 gives;

$$A_s \quad \propto \frac{P^{1/3}\,Q}{D^{2/3}} \quad \textit{Expression 3.4-2}$$

The amount of heat absorbed by the sprinkler spray will depend on the total surface area of all the water droplets, as shown in expression 3.4-2 above, and the difference in temperature between the droplets and the ceiling hot gas layer.[30] The depth of the hot gaseous layer on the ceiling plume will also have an effect on the rate at which heat can be absorbed by the sprinkler spray.

Sprinkler suppression or control is achieved by a combination of mechanisms. In addition to producing cooling the discharged sprinkler droplets can assist in suppression by the depletion of oxygen from the surrounding area.[30] This suppression mechanism is applicable to small enclosed sprinkler protected areas. In this scenario the droplets discharged by the sprinkler are expanded to approximately 1,700 times their original volume as they are converted into water vapor. The expanded water vapor depletes the oxygen around the fire area, thus assisting suppression.[30]

Sprinkler control of the fire is achieved by the combination of the sprinkler heads directly over the fire operating and the adjacent heads pre-wetting the fuel. In order to achieve fire control two energy balances must simultaneously occur, one at high level and one at the seat of the fire.

At the seat of the fire sufficient water, with the correct droplet size, must be applied to reduce the rate of combustion. At high level the spray from the sprinklers must have enough cooling effect to absorb the heat of the fire plume and prevent the operation of unnecessary adjacent sprinklers. If too many sprinklers are operated the sprinklers over the fire area will not be able to apply sufficient density, hence the fire will continue to grow and control will be lost.[30]

3.5 Sprinkler Suppression Model

It is useful to be able to conservatively estimate the effectiveness of sprinklers in reducing the heat release rate of a fire. Evans has published an equation for the aforementioned scenario which was derived by combining the results of previous experimental work undertaken by Madrzykowski & Vettori, and Walton & Tamanini.[34] The experimental fire tests utilised a fuel package consisting of either a 305mm or 610mm square wood crib. Suppression was achieved using a standard pendant spray type sprinkler.

Madrzykowski & Vettori formulated a generic conservative equation for the reduction in heat release rate for a series of various fuel packages. Their resulting equation is of the following form:-

$$\dot{Q}\ (t-t_{act})\ /\ \dot{Q}\ (t_{act}) = \exp\left[\ -\ (t-t_{act})\ /\ 435\ \right] \quad \text{Equation 3.5-1}$$

Where,

$\dot{Q}\ (t-t_{act})$ = post sprinkler activation heat release rate of the fire, kW

$\dot{Q}\ (t_{act})$ = heat release rate at the time of sprinkler activation (t_{act}); kW

This prediction has limitations as it is not applicable when the fuel is shielded from the sprinkler spray pattern, or if the application density is less than 4.2 $l/min/m^2$. In addition to the above, the method proposed by Madrzykowski & Vettori does not accommodate for variations in sprinkler density.

Walton[35] undertook a series of tests of wood crib fires, which did account for variations in sprinkler density. Walton's results gave an equation of the form.[34]

$$\dot{Q}\ (t-t_{act})\ /\ \dot{Q}\ (t_{act}) = \exp\left[- (t-t_{act})\ /\ \tau \right] \quad \text{Equation 3.5-2}$$

In equation 3.3-2 above, τ is a time constant for the post sprinkler activation, heat release rate reduction.

Experiments conducted by Tamanini found that the time to extinguish a wood crib fire was proportional to the water application rate per unit of exposed surface area.

Evans superimposed the finding of Walton's study on Tamanini's results by normalising the crib height. These combined results gave a "best fit" prediction for the time constraint as

$$\tau = 2.0 \times 10^{-5}\ (\dot{W}''\ /\ Hc)^{-1.85} \quad \text{Equation 3.5-3}$$

Where,

τ = *time constant (s)*

$\dot{W}''$ = *spray density (l/min/m²)*

Hc = crib height (mm)

By substituting a value of 610mm for the crib height into equation 3.5-3, equation 3.5-2 can be rewritten as;

$$\dot{Q}\ (t-t_{act}) = \dot{Q}\ (t_{act})\ \exp\left[- (t-t_{act})\ /\ (3.0\ /\ \dot{W}'')^{-1.85}) \right] \quad \text{Equation 3.5-4}$$ [34]

Equation 3.3-4 can be used to predict the reduction in the fire heat release rate of a wood crib or furnishing fire during the suppression period, when water is applied from a standard spray type sprinkler.[34]

Limitations exist to equation 3.5-4, as per Madrizykowski's & Vettori's equation, however spray density is accounted for.

Figure 3.5-1below shows the results obtained by Walton with a 610mm wood crib fuel package. The results demonstrate the higher application density, the superior the rate of heat release reduction. Walton found that extremely low application densities (ie., 2.34 l/min/m^2) had no effect on the rate of heat release reduction.[35]

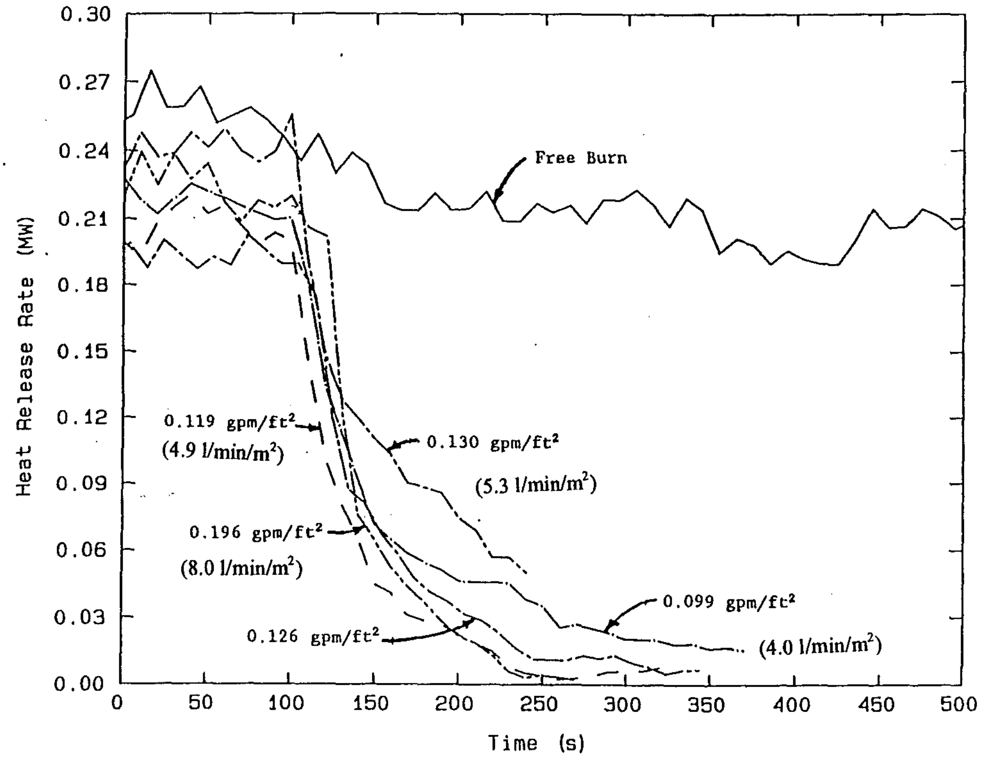


Figure 3.5-1: 610mm wood crib heat release rates at varying densities.[35]

3.6 Class A Foam Suppression

Class A foam concentrate is formulated from a mixture of specific hydrocarbon surfactants, stabilizers, inhibitors and solvents.[4, 37] Appendix 1 lists the physical properties of various Class A foam concentrates.

The addition of Class A foam concentrate to water alters the surface tension of the resultant solution. Figure 3.6-1 below outlines the resultant surface tension values for Class A foam solution.

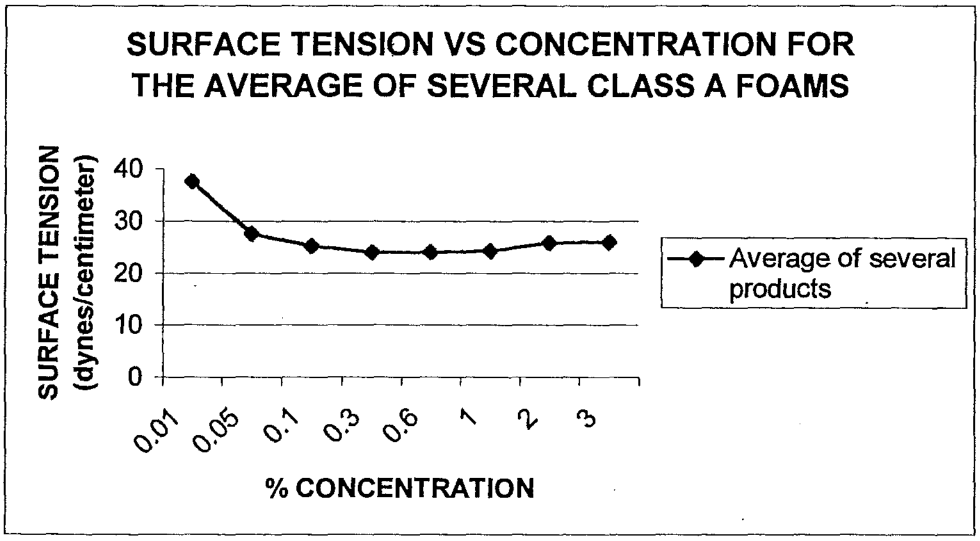


Figure 3.6-1: Surface tension valves for water and Class A foam solution.[36]

Note: ***Full details are given in Appendix 1.***

The high surface tension properties of water causes the formation of large droplets or beads. The formation of these larger droplets limits the contact surface area between the water and the combustion fuel interface, thereby restricting the fire suppression ability.[37]

Class A foam solution, with its low surface tension, has the physical structure to spread easily over the fuel and deeply penetrate the combustion char layer.[37, 38] The increased surface area between the suppression agent and the fuel will increase the rate of heat absorption.[38]

The addition of class A concentrate to water in low proportions (ie., 1%) does not significantly alter the specific heat capacity of the solution. Experiments conducted on two class A 1% solutions resulted in specific heat values of 4.17 J/g/K and 4.06 J/g/K respectfully. Pure water has a specific heat value of 4.186 J/g/K.[39]

Infrared imaging techniques conducted with droplets of pure water and class A solution deposited onto a hardboard surface, show that the penetration rates of the two mediums are within 10% of one another. These infrared tests also indicate that the average cooling rate of a class A solution should be about 1.5 times that of pure water. This theoretical increased cooling rate is explained by the increased area of coverage associated with the surfactants present in the solution. The infrared imaging techniques demonstrated that the relative area of coverage of the solutions was approximately 4 times that of the water, which remained "beaded" as a result of its high surface tension.[39]

NIST laboratory tests[39] evaluated the contact surface angle between droplets of foam solution and several material surfaces. These tests were conducted in order to quantify the "wettability" of various class A solutions. The contact angle is defined as the angle between the surface and the tangent line at the point of contact. Figure 3.6-2 below defines the surface contact angle. The experiment used a contact angle meter to determine the surface interface angles.

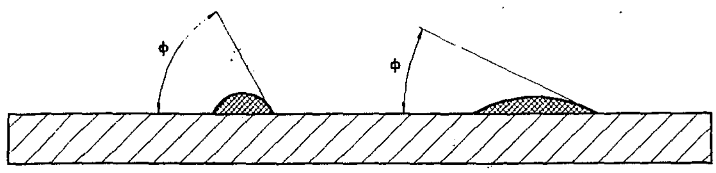


Figure 3.6-2: Surface Contact Angle.

The experiments found that the class A foams had significantly reduced contact angles compared to that of pure water. This property leads to a droplet of class A solution covering a larger surface area compared to pure water, hence the rate of cooling will be increased.[39]

The reduced surface tension of class A foam solutions has the potential to produce smaller droplets when mechanically adjacated by a fire fighting nozzle or sprinkler head, compared to plain water. The increased number of smaller droplets would provide an overall greater surface area, hence theoretically class A foam solutions would have superior cooling properties. Experimental work has been undertaken to examine the droplets produced by a typical fire fighting fog nozzle (at 690kPa and 36 l/min) with both plain water and various class A solutions. In this study droplet measurements were made with an optical laser probe with the capacity to measure droplets in the range of 30 μm to 1860 μm. The experiment produced data for the Dv0.5, Dv0.9 and Dv0.99 for the different agents and plain water at various distances from the centre line of an overhead nozzle. These tests found that all the agent solutions tested produced different results. In brief, the droplet diameters of a foam solution produced by a typical fire fighting nozzle maybe larger or smaller than the droplets formed from pure water.[39] The droplet diameters formed will vary with the different manufacturers agent formulations.

Colletti claims that the hydrocarbon surfactants within class A foams will be attracted to the carbon compounds present in a class A fuel, and will therefore form a cooling foam blanket which allows the solution to cling to the surface and provide cooling and fuel penetration over an extended period of time.[37]

Secondary fire suppression mechanisms associated with class A foam include; the suppression of gaseous combustion products by the foam layer and the reflection of heat by the white foam.[37, 38]

To date no mathematical model exists for foam extinguishment. Any future models must be based on experimental work.[40]

3.7 *Foam Expansion Ratio And Its Effect On Suppression*

The proportioning ratio for class A foam solutions varies from 0.1% to 1%, depending on the nature of the fuel being protected and the application hardware.

Aspirated foam is formed by the addition of air to foam solution prior to application discharge. For manual fire fighting purposes this is achieved by using an aspirating type discharge nozzle or by injecting compressed air into the foam solution as in the case of a CAFS system.

Foam water deluge systems utilise an aspirating type sprinkler head. These sprinkler heads aspirate the foam by either entraining air into the foam solution or by mechanical adjacation using a mesh type of diffuser. Figure 3.7-1 shows a typical foam water sprinkler. Foam solution is first transformed into spray. The velocity of the solution then acts to entrain the surrounding air through a venturi action.

This aspirated foam is developed in a mixing chamber. Upon exiting the mixing chamber the aspirated foam solution is directed to the deflector which distributes the suppression agent to the fire. This type of head requires a minimum pressure of about 207 kPa in order to be effective.[40]

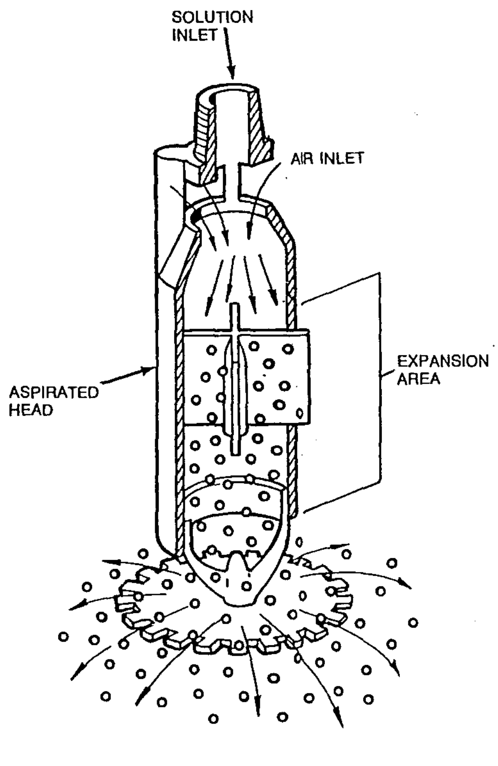


Figure 3.7-1: Aspirated foam formation for a foam water sprinkler.[41]

A mesh type diffuser head as shown in figure 3.7-2 can be used to form aspirated foam. This type of head is dependent on mechanical interaction between the foam solution and mesh, to break the foam solution stream and aspirate the individual droplets.

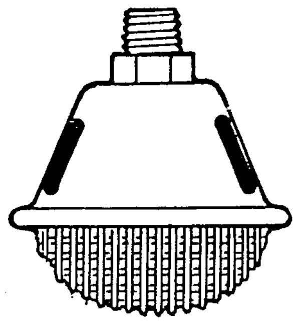


Figure 3.7-2: Mesh type diffuser aspirating head.

Based on current technology no closed head aspirating foam sprinkler exists. For this reason closed head foam water sprinkler systems currently use standard spray type sprinkler heads.

The expansion ratio of an aspirated foam is defined as, the ratio of final foam volume to the original foam solution volume, as in accordance with NFPA-11.[42] In mathematical form this relationship can be represented as;

$$E = \frac{Va + Vfs}{Vfs} \qquad \text{Equation 3.7-1}$$

Where,

E - expansion ratio

Va - volume of air

Vfs - volume of foam solution

A low expansion foam is defined as having an expansion ratio of less than 20.[42] The various foam generating hardware arrangements such as CAFS, foam-water aspirating sprinklers and standard sprinklers, all generate low expansion finished foams. The typical expansion ratios associated with the various hardware arrangements varies considerably as listed in table 3.7-1.

Hardware Device	Typical Expansion Ratio
Foam-Water Sprinklers *	3.4:1 - 4.3:1
Standard Spray Sprinklers *	2.2:1 - 2.3:1
Compressed Air Foam System +	4:1 - 20:1

Notes * *Tests undertaken with AFFF for Hangar deluge systems tested by Factory Mutual Research Corporation*[40]
+ *Tests undertaken with AFFF produced by a fixed overhead CAFS*[44]

Table 3.7-1: Foam expansion ratios for various discharge hardware devices.

The optimum foam expansion rate will vary for different fuel applications.[38] The suppression of a deep seated class A fire is best achieved by using a non-aspirated, or low expansion type, foam. In this situation the reduced surface tension of the class A foam solution permits deeper penetration into the char layer and maximises the wetting surface area.[37, 38]

Aspirated foam is best applied when exposure protection is required.[37, 43] Aspirated type foams are more viscous than non-aspirated foams, and tend to adhere well to vertical surfaces.[38] The aspirated foam layer forms a vapor seal on the fuel that contributes to extinction by removing oxygen from the fuel interface boundary.[38] A secondary suppression characteristic of aspirated foam is the ability of the foam layer to insulate the fuel from the heat and flames of the fire. The foam layer acts as a barrier by preventing radiation from the flame reaching the fuel. This characteristic makes aspirated foam ideal for providing exposure protection.[37] Aspirated foam, with its developed bubble structure array, provides a slow draining supply of water to cool the fuel.

3.8 Aspirated Foam Stability

Kim et al[44] has documented recent theories on aspirated foam stability and collapse based on the findings of previous work undertaken by Lemlich, Durian, Sita et al and Guraray et al.

The formation of aspirated foams, by hardware devices such as sprinklers and aspirating fire fighting nozzles, typically produces a finished foam with a large foam water distribution of bubble sizes. Smaller bubbles have higher internal gas pressures than larger bubbles. This pressure difference causes diffusion from small bubbles to larger bubbles, where the rate of diffusion is proportional to the difference in pressures within the foam bubbles.

From Laplace & Young's law, it follows that[44];

$$\Delta P = 2\gamma\left(\frac{1}{r_s} - \frac{1}{r_\ell}\right) \quad \textit{Equation 3.8-1}$$

Where,

ΔP	=	*pressure difference*
γ	=	*surface tension*
r_s	=	*small bubble radius*
r_ℓ	=	*large bubble radius*

Lemlich formulated an expression for the change in size of a single bubble;

$$\frac{dr}{dt} = K\left(\frac{1}{r_{12}} - \frac{1}{r}\right) \quad \textit{Equation 3.8-2}$$

Where,

r	=	*bubble radius*
K	=	*proportionality constant (inclusive of* ΔP*)*
$r_{12}(t)$	=	$\dfrac{\int_0^\infty r^2F(r,t)dr}{\int_0^\infty rF(r,t)dr}$
$F(r,t)$	=	*bubble size distribution function*

Equation 3.8-2 demonstrates that aspirated foams with a large bubble distribution size will decay more rapidly due to the internal pressure differences. This scenario results in increased drainage rates, as the foam solution film decays to form plateau borders which join to form a drainage network[44].

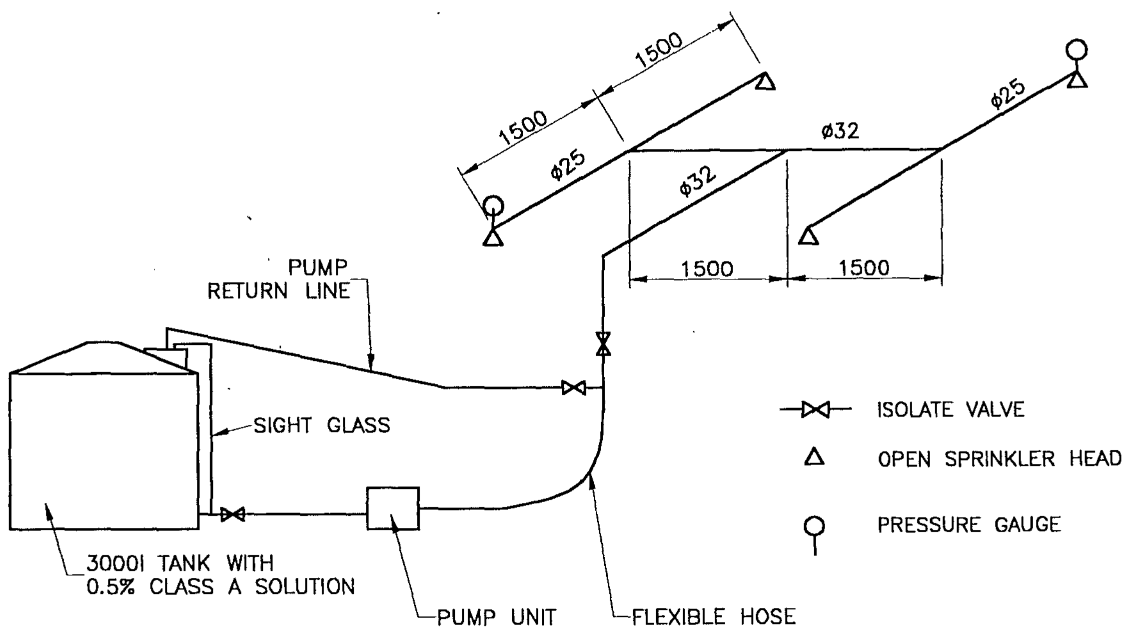
CHAPTER 4.0 EXPERIMENTAL APPARATUS

4.1 Foam Expansion Tests

All tests were performed in the Pipe Fabrication Workshop of Tyco New Zealand Limited, situated in New Lynn, Auckland.

A 3000 litre capacity polyethylene plastic tank was provided for the storage of the foam solution. The tank had a 50mm nominal bore outlet to which a sight glass and isolate valve were fitted. The tank was coupled to a petrol driven pump unit. 50mm nominal bore spring reinforced hoses, with instanéous couplings were used on the suction and discharge side of the pump. A bypass line and associated isolate valve were installed to enable the tank contents to be recirculated and to assist with the balancing of the required discharge flow rates. An isolate valve was installed on the main pipework riser. This valve would enable the flow to the array to be throttled to facilitate pressure balancing. Figure 4.1-1 shows a schematic of the test arrangement.

Figure 4.1-1: Schematic Representation of the Test Configuration.



Ansul "Silv-ex" type class A foam concentrate was used in all of the tests. The concentrate was added to ordinary tap water in the tank to give a 0.5% foam solution. A three litre capacity graduated laboratory measuring jug was used to measure the quantity of concentrate added to the water.

A balanced pipework array was constructed in accordance with UL standard 199, Part 31.[32] This array had the capacity to flow four sprinklers. The array was suspended from a bracket arrangement which was fixed to the floor and the adjacent side wall of the workshop. Two pressure gauges, complete with gauge snubbers, were fixed to the sprinkler tees at opposite ends of the array.

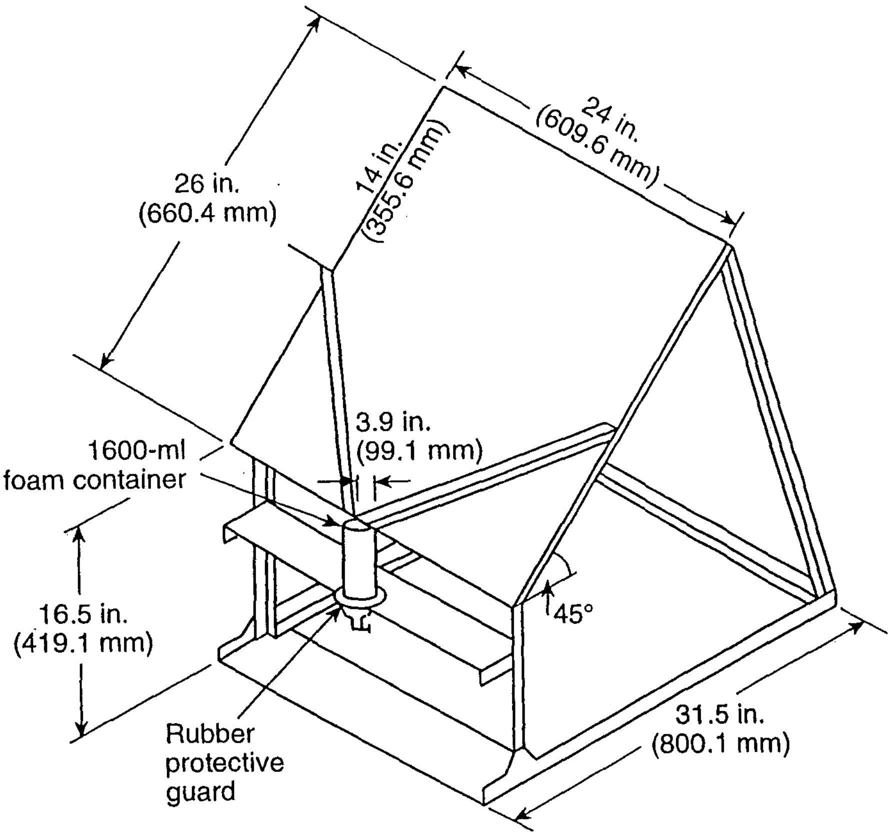
A foam slider board and collector, manufactured in accordance with the guidelines detailed in chapter 11 of NFPA standards,[42] was used for collecting the expanded foam solution from the overhead sprinkler array. Analysis of the discharged foam solution was undertaken using an electronic scale balance, stop watch and graduated cylinder.

To assist in the containment of the discharged foam solution the perimeter of the test area was boxed out with a temporary rough sawn timber nib wall, of approximately 200mm in height. A plastic liner was placed on the floor and fixed to the timber nib wall arrangement to provide a dam to contain the discharged solution. At one end of the test area sandbags were positioned to enable the drainage of the foam solution directly into an inlet of the towns sewer network. Table 4.1-1 lists a summary of the equipment used in the foam expansion experiments.

Table 4.1-1: Summary of equipment used in the Foam Expansion Experiments.

COMPONENT	DESCRIPTION
Foam Slider - collector board	Manufactured in accordance with NFPA-11 (refer to figure 4.1-2 for details)
Solution Storage Tank	3000 litre capacity polyethylene plastic tank, 1800mm nominal diameter, 1500mm high manufactured to ASTMD standard 1998-91.
Pump Unit	Wacker model PT2 centrifuged pump directed coupled to a Honda 5Hp model GX140 petrol powered internal combustion engine.
Weighing Scales	Toledo electronic scales, model no. 8581.
Pressure Gauges	Gauge 1 0-250kPa, 100mm full face, liquid filled. Gauge 2 0-160kPa, 100mm full face, liquid filled.
Pipework	Manufactured to BS 1387 - medium grade, mill galvanised.
Measuring Devices	• 1000ml capacity scientific graduated measuring cylinder. • 500ml capacity scientific graduated measuring cylinder.
Foam Concentrate	Ansul Silv-ex (0.5% solution).

Figure 4.1-2: Foam Slider Collector Board.

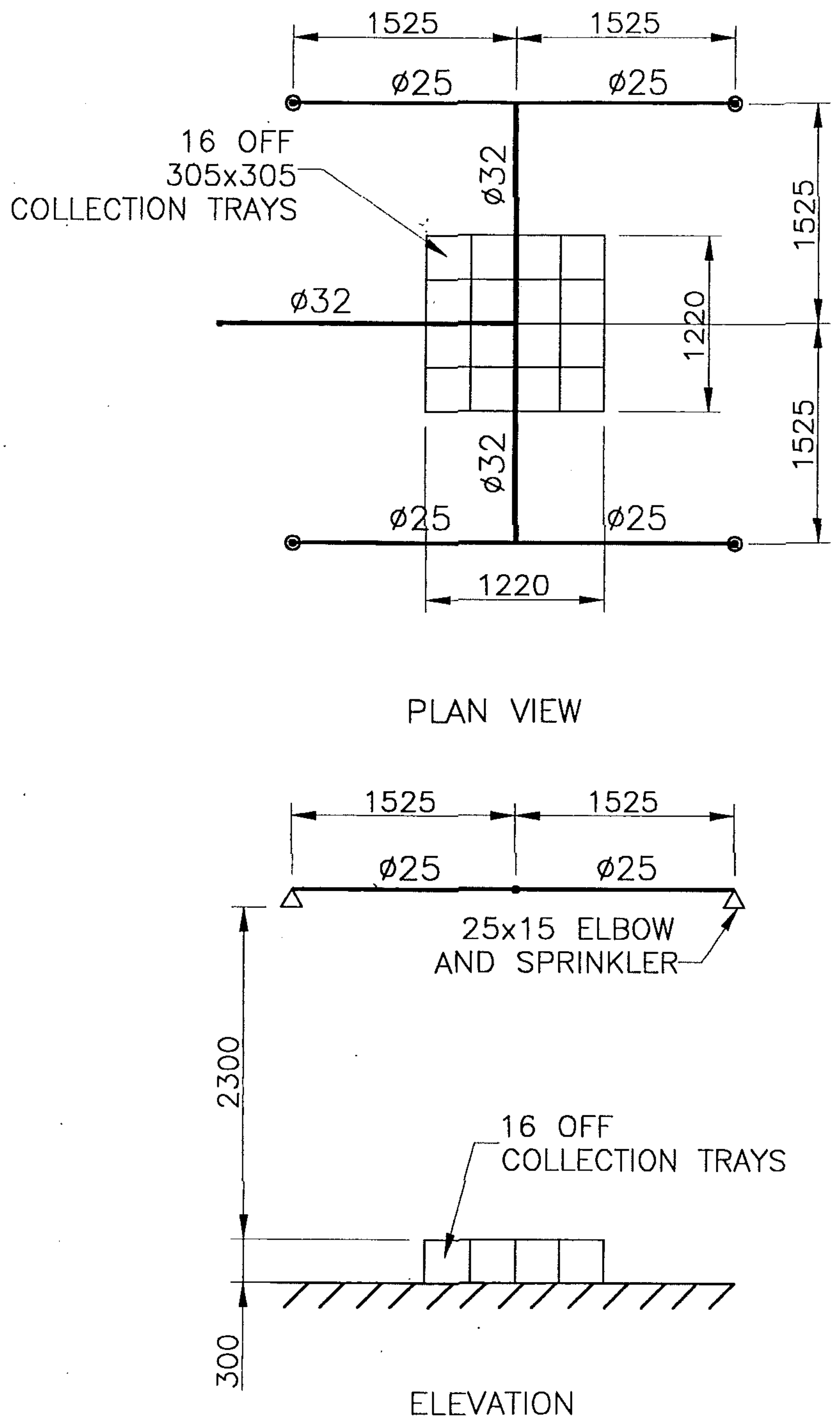


4.2 Foam Distribution Tests

The same test configuration was used for foam solution distribution tests as described in section 4.1 above. The distribution tests were based on the UL standard 199, 16 pan method.[32] Sixteen open collection pans with dimensions, (305mm x 305mm x 305mm), were located under the centre of the array as shown in figure 4.2-1. Foam solution was supplied from the tank and pump arrangement, described in section 4.1 above.

The electronic scale, described in table 4.1-1, was used to determine the mass of the pans before and after the solution was discharged through the overhead array.

Figure 4.2-1: Foam Distribution Test Array.



CHAPTER 5.0 EXPERIMENTAL PROCEDURE

5.1 Foam Expansion Tests

A series of tests were conducted to investigate the relationship between sprinkler head discharge pressure and foam expansion ratio.

Water was added to the storage tank and the volume calculated by measuring the height of water added and knowing the diameter. The required amount of foam concentrate was added to give a 0.5% foam solution. With the sprinkler array isolate valve closed and the bypass valve opened the pump was started to enable the solution to be circulated and uniformly mixed. The bypass valve was closed following this task.

For each of the foam expansion tests the pump was started and the pipework array isolate valve slowly opened until a steady state condition at the desired test pressure was obtained. The two pressure gauges, located on the opposite sides of the array were monitored for the desired pressure and adjustments made to the isolate valve if required.

Prior to undertaking the tests the mass of the collector stand and the empty collector were determined. The collector was filled with tap water and weighted, in order to determine its capacity.

The collection and analysis of the expanded foam was carried out in accordance with the test procedures detailed in chapter 11 of NFPA standards.[42] Upon a steady state condition being reached at the desired test pressure, the foam container was positioned in the foam-slider collection apparatus. The container was removed from the foam-slider apparatus and discharge area once it was full. Care was taken to avoid spillage and additional solution from entering the container during its removal from the discharge area. Using a dry cloth the solution on the outside was wiped of the collection container. The container was placed on a purpose built stand on the electronic scales in order to measure the gross mass of the stand, foam collector and expanded solution.

Tests to determine the 25% drain time were performed by two methods. In the case of fast draining foams, initially a 500ml calibrated container was used (ie., Tests 1-3). For later tests a 1000ml graduated measuring cylinder was used. Times were recorded for the drained solution to reach various levels in the measuring cylinders. For tests (12-17) the hindsight of experience showed that the above method was not ideal. A large proportion of the solution drained contained expanded foam, hence the drained volume did not equate to the weight of solution present. For these tests the decrease in mass of the original solution was recorded at various time intervals. All expansion and 25% drain tests involved two personnel.

Due to the limiting characteristics of the pump performance curve the number of sprinklers flowed within the array varied depending on the desired head pressures. In the case where low pressures were required (ie., 50kPa) all four heads were operated. Foam expansion tests were also conducted with two and single heads operating. In these situations the redundant sprinkler elbows were plugged.

When four and two heads were operated the foam-slider collector board was located in the centre of the array. Single head tests were conducted with the foam-slider collector board located at a radius of 1.2m from the centre line of the sprinkler deflector and orientated so the slope of the board faced the discharging head, (refer to figures 5.1-1(a) and (b)).

In all tests the frame arms of the individual sprinklers were orientated parallel with branch lines.

Additional foam expansion tests were performed on foam-water type sprinklers and large drop, high challenge type sprinklers. Both of these heads operate a high discharge pressures. Ideally it would have been advantageous to test these heads at a range of elevated pressures, however due to the limiting capacity of the pump the heads were only tested at the highest pressure available.

Figure 5.1-1(a): Position of Foam-Slider when operating 4 and 2 sprinklers.

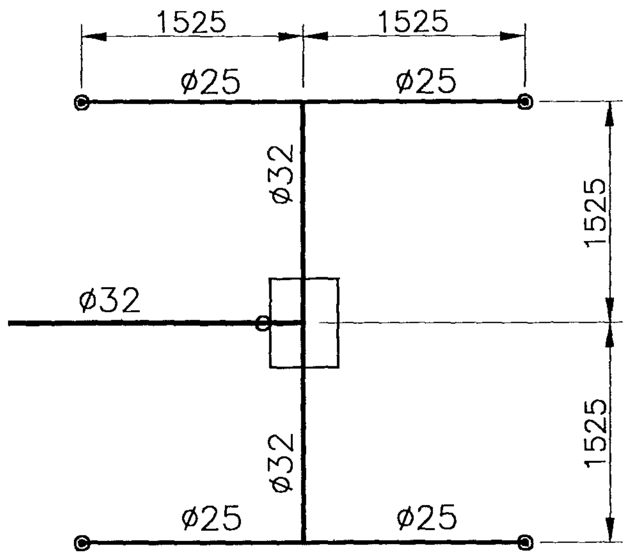
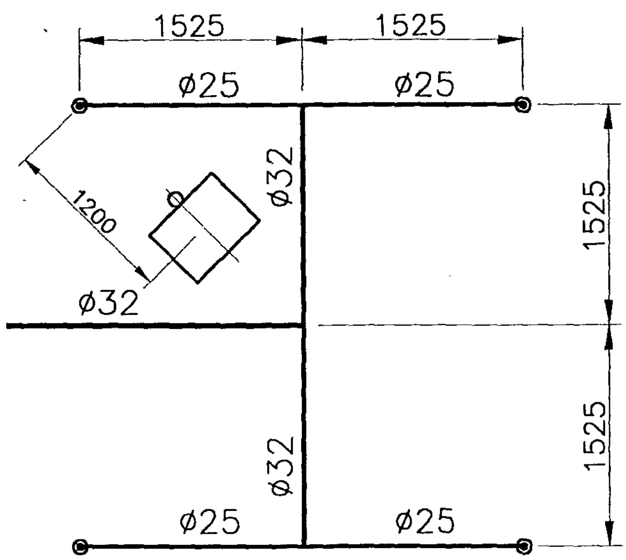


Figure 5.1-1(b): Position of Foam-Slider when operating a single sprinkler.



5.2 *Foam Distribution Tests*

Foam distribution tests were conducted in accordance with UL standard 199, 16 pan method.[32] Four, 15mm nominal bore orifice spray type pendant sprinklers were operated at a pressure of 52kPa in order to give the required test flow rate.

Preliminary discharge tests were conducted to obtain a steady state pressure of 52kPa at the sprinkler heads. Following this task the sprinkler/gauge tee fittings on the discharge array were replaced with reducing elbows as per the requirements of UL standard 199.[32]

The 16 collection pans were initially permanently numbered and their dry weights recorded. The empty pans were located in the centre of the discharge area and butted together in a four by four array. A plumb bulb was used to check that the centre of the pan array was located in the centre of the discharge pipework configuration.

The initial level of the foam solution storage tank was recorded. This step was performed as a check on the overall flow rate, since the discharge time and final tank solution level could also be determined.

The stop watch was started at the commencement of the flow of solution through the sprinklers. The pump was allowed to run for a period of approximately 10 minutes in accordance with UL-199.[32] (Refer to chapter 6 for details).

The outside surfaces of the individual collection pans were first dried with a cloth and their gross weights recorded. The final level of the foam solution storage tank was recorded. The tank was refilled with foam solution and the test repeated after sprinkler heads on the opposite ends of the discharge array were transposed.

CHAPTER 6.0 RESULTS AND OBSERVATIONS

6.1 Foam Expansion Tests

Preliminary data derived was as follows:-

- Mass of foam collector and tail tube (empty), valve and stand = 4.520 kg.
- Mass of foam collector and tail tube (fill with tap water), valve and stand = 6.310 kg.
- Calculated capacity of foam collector and tube = 1.790 litres (1.790 kg).

$$\text{Expansion ratio} = \frac{\text{Capacity of container (kg)}}{\text{Net mass of expanded foam (kg)}}$$

Table 6.1-1 lists a summary of the foam expansion tests for the various sprinklers tested.

Table 6.1-1: Results of Foam Expansion Tests:-

TEST NO.	SPRINKLER TYPE	PRESSURE AT HEAD (kPa)	NO. OF HEADS OPERATING	GROSS MASS (KG)	NETT MASS (KG)	EXPANSION RATIO
1	GEM A 15mm SSP	85	4	5.365	0.845	2.12
2	GEM A 15mm SSP	85	4	5.305	0.785	2.28
3	GEM A 15mm SSP	48	4	5.660	1.140	1.57
4	GEM A 15mm SSP	50	4	5.520	1.000	1.79
5	GEM A 15mm SSP	110	2	5.300	0.780	2.29
6	GEM A 15mm SSP	130	2	5.325	0.805	2.22
7	GEM A 15mm SSP	130	2	5.330	0.81	2.21
8	GEM A 15mm SSP	180	1	5.335	0.185	2.20
9	GEM A 15mm SSP	172	1	5.395	0.875	2.05
10	GEM A 15mm SSP	172	1	5.470	0.950	1.88
11	GEM F/W 10mm B-1	220	1	5.185	0.665	2.69
12	GEM F/W 10mm B-1	206	1	5.160	0.64	2.80
13	GEM F/W 10mm B-1	206	1	5.135	0.615	2.91
14	GEM F/W 10mm B-1	206	1	5.135	0.615	2.91
15	VIKING L/D 20mm	112	1	4.995	0.475	3.77
16	VIKING L/D 20mm	110	1	5.145	0.625	2.86
17	VIKING L/D 20mm	110	1	5.180	0.66	2.71

Notes on table 6.1-1.

~ GEM A 15mm SSP;- GEM type model A 15mm nominal bore orifice spray type sprinkler pendant.

~ GEM F/W 10mm;- GEM Model B1 foam-water sprinkler, 10mm nominal bore orifice, pendant sprinkler.

~ Viking L/D 20mm;- Viking type high challenge, large drop type head, upright.

Figure 6.1-1: Expansion Ratio as a Function of Pressure.

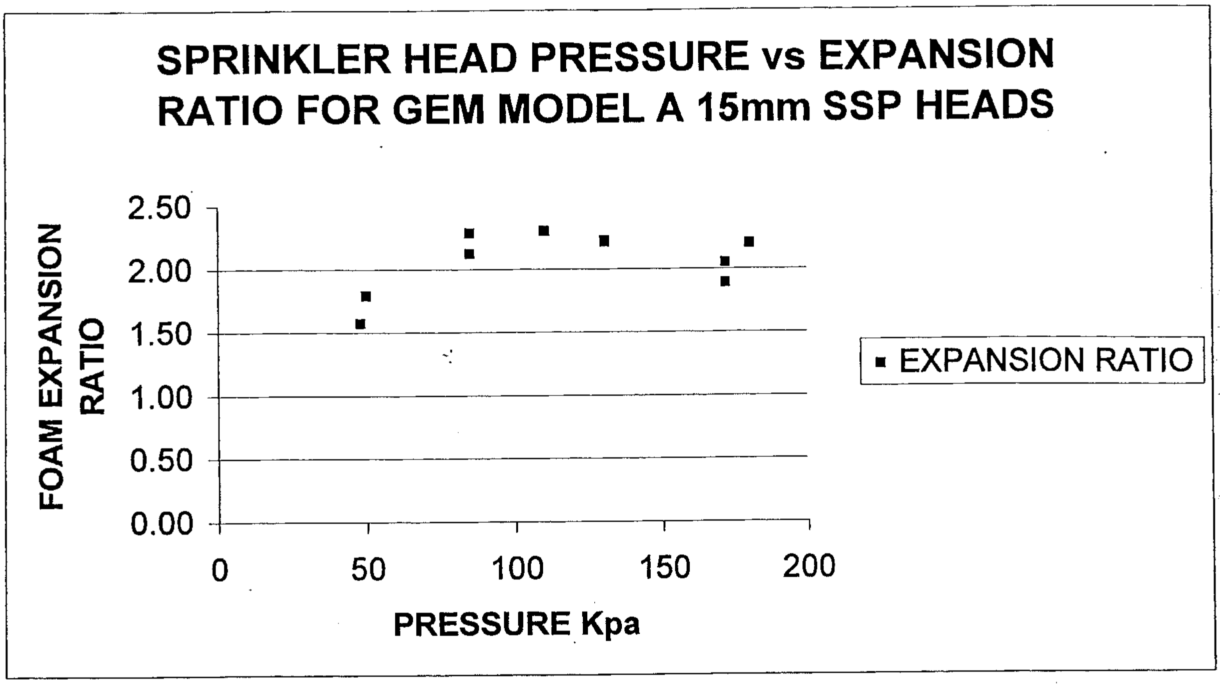
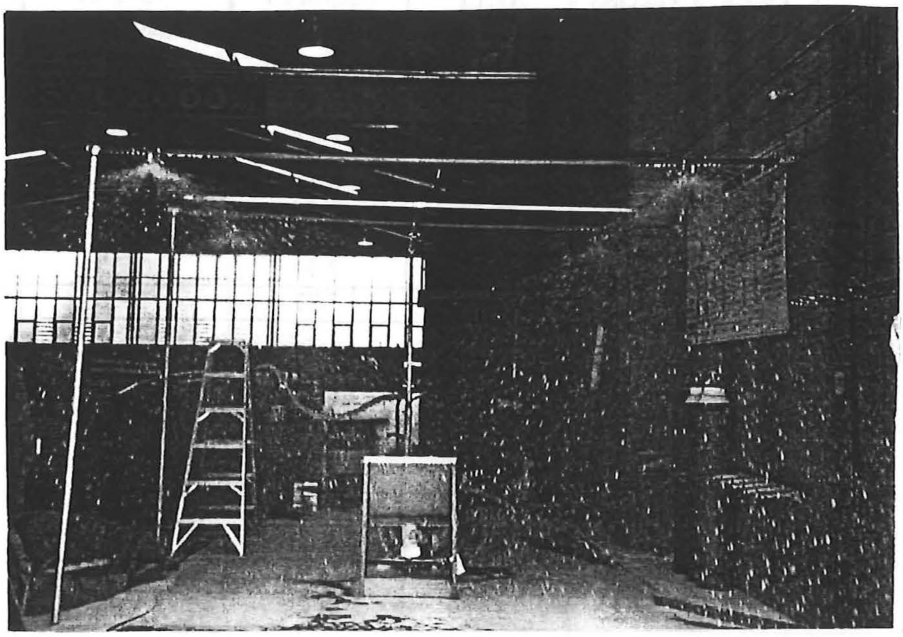


Table 6.1-2: Results of 25% Drain Tests.

TEST NO.	SPRINKLER TYPE	PRESSURE AT HEAD (kPa)	NO. OF HEADS OPERATING	EXPANSION RATIO	25% DRAIN TIME (Sec)
1	GEM A 15mm SSP	85	4	2.12	15
2	GEM A 15mm SSP	85	4	2.28	13
3	GEM A 15mm SSP	48	4	1.57	21
4	GEM A 15mm SSP	50	4	1.79	25
5	GEM A 15mm SSP	110	2	2.29	17
6	GEM A 15mm SSP	130	2	2.22	18
7	GEM A 15mm SSP	130	2	2.21	12
8	GEM A 15mm SSP	180	1	2.20	16
9	GEM A 15mm SSP	172	1	2.05	12
10	GEM A 15mm SSP	172	1	1.88	13
11	GEM F/W 10mm B-1	220	1	2.69	14
12	GEM F/W 10mm B-1	206	1	2.80	17
13	GEM F/W 10mm B-1	206	1	2.91	31
14	GEM F/W 10mm B-1	206	1	2.91	36
15	VIKING L/D 20mm	112	1	3.77	14
16	VIKING L/D 20mm	110	1	2.86	6
17	VIKING L/D 20mm	110	1	2.71	22

Figure 6.1-2: Foam Expansion Tests (Test No. 4, 50 kPa).



6.2 Foam Expansion Tests

Foam distribution tests were undertaken with four GEM Model A spray type sprinkler heads operating at a pressure of 52kPa. The results of the tests are shown in tables 6.2-1 and 6.2-2. It should be noted that UL Standard 199 requires that a minimum area density of 6.112 l/min/m^2 be achieved and that all of the pans shall achieve at least 75% of this minimum valve.

Table 6.2-1: Foam Distribution Test Number 1 - Results.

TRAY NO.	TRAY MASS (Kb)	GROSS MASS (Kg)	NETT MASS (Kg)	DENSITY L/min/M^2	>75% OF MINIMUM
1	3.210	8.900	5.690	6.23	YES
2	3.210	9.435	6.225	6.82	YES
3	3.230	10.020	6.790	7.44	YES
4	3.215	9.135	5.920	6.48	YES
5	3.215	11.770	8.555	9.37	YES
6	3.215	12.555	9.340	10.23	YES
7	3.220	11.725	8.505	9.31	YES
8	3.220	10.100	6.880	7.53	YES
9	3.210	12.695	9.485	10.39	YES
10	3.220	14.045	10.825	11.85	YES
11	3.220	11.545	8.325	9.12	YES
12	3.210	9.540	6.330	6.93	YES
13	3.225	11.115	7.890	8.64	YES
14	3.225	11.640	8.415	9.21	YES
15	3.220	9.930	6.710	7.35	YES
16	3.210	8.840	5.630	6.17	YES
TOTAL			121.515		
AVERAGE				8.317	
MINIMUM SPECIFIED				6.112	
75% MINIMUM				4.584	

Table 6.2-2: Foam Distribution Test Number 2.

TRAY NO.	TRAY MASS (Kb)	GROSS MASS (Kg)	NETT MASS (Kg)	DENSITY L/min/M^2	>75% OF MINIMUM
1	3.210	7.83	4.620	4.89	YES
2	3.210	9.41	6.200	6.57	YES
3	3.230	9.55	6.320	6.69	YES
4	3.215	7.365	4.150	4.40	NO
5	3.215	8.75	5.535	5.86	YES
6	3.215	10.145	6.930	7.34	YES
7	3.220	10.52	7.300	7.73	YES
8	3.220	8.37	5.150	5.45	YES
9	3.210	9.005	5.795	6.14	YES
10	3.220	11.905	8.685	9.20	YES
11	3.220	15.645	12.425	13.16	YES
12	3.210	13.485	10.275	10.88	YES
13	3.225	8.51	5.285	5.60	YES
14	3.225	11.375	8.150	8.63	YES
15	3.220	17.59	14.370	15.22	YES
16	3.210	16.32	13.110	13.88	YES
TOTAL			124.300	131.65	
AVERAGE				8.228	
MINIMUM SPECIFIED				6.112	
75% MINIMUM				4.584	

Figure 6.2-1: Foam Distribution Test Number 1.

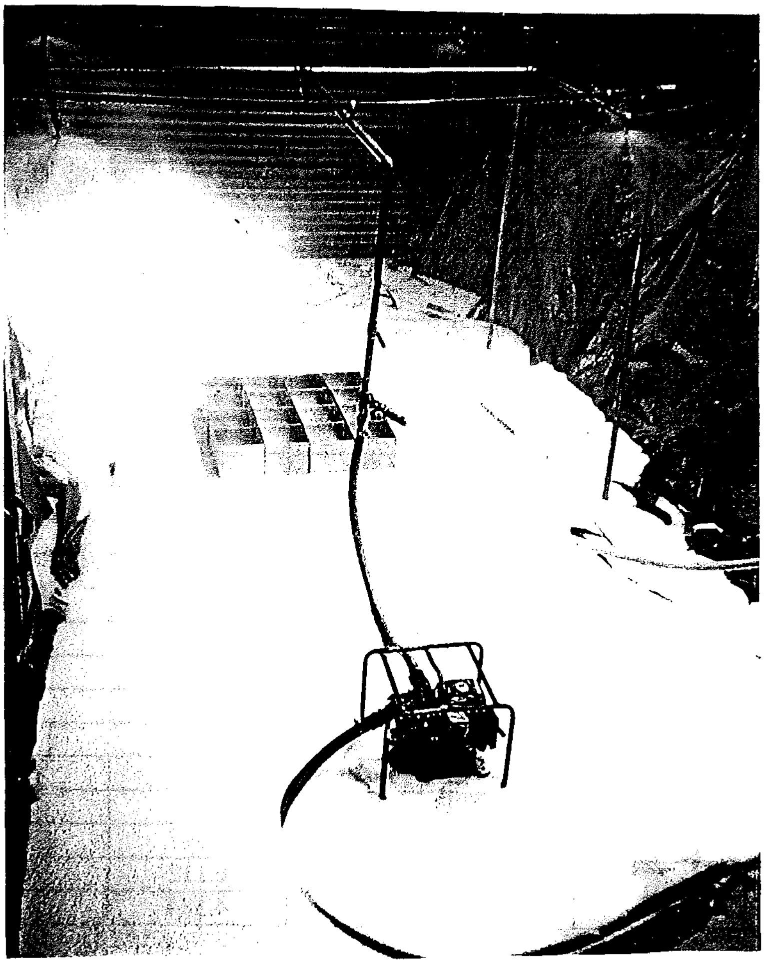
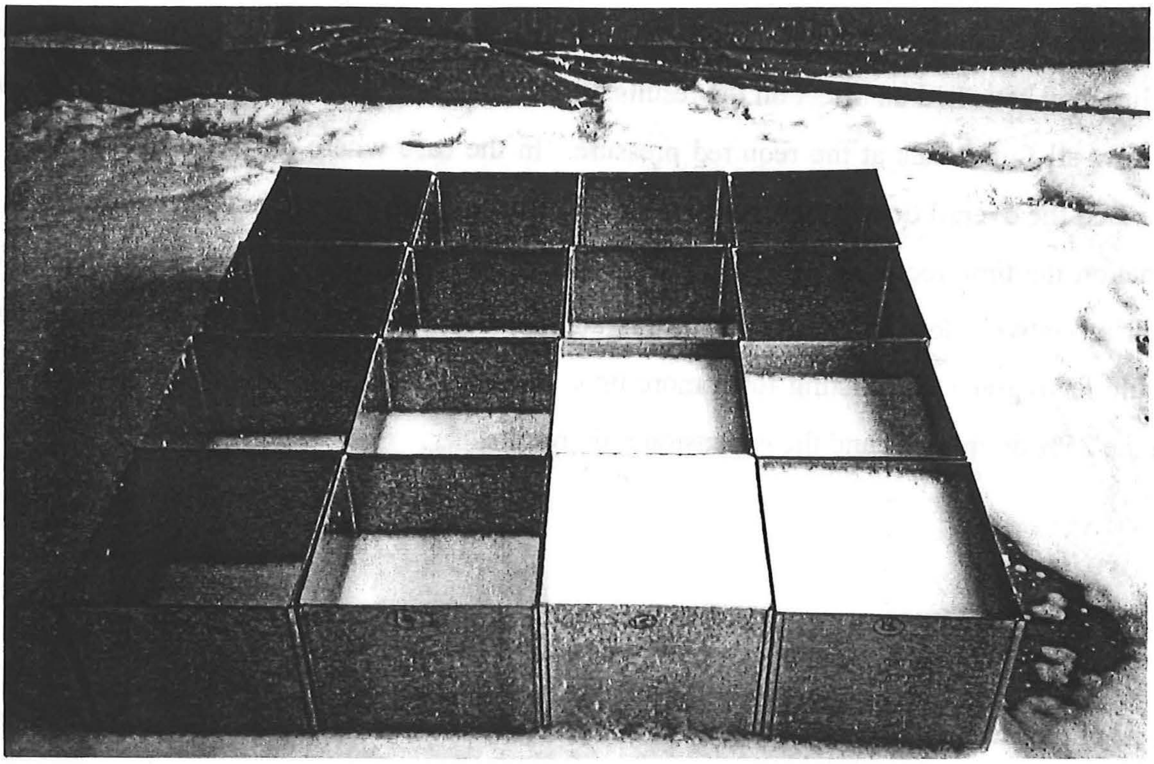


Figure 6.2-2: Foam Distribution Test Number 2.



6.3 Discussion

- **Foam Expansion Tests**

Figure 6.1-1 indicates that there is an increase in the foam expansion ratio when the applied pressure is increased from 50kPa to 85kPa. Beyond this pressure, higher expansion ratios were not obtained with further pressure increases.

The results of any previous experimental work relating to foam expansion, with class A foam and standard sprinklers, could not be found. Tests undertaken by Factory Mutual Research Corporation with 3% AFFF foam solution and standard sprinklers resulted in expansion ratios in the range of 2.2-2.3.[40] These tests were conducted at a pressure of 97kPa and an elevation of 18.3m. These results are very similar to the tests undertaken in this research at a similar pressure, (ie., tests 1 and 2 gave expansion ratios of 2.12 and 2.28 at a pressure of 85kPa).

There is a significant difference between the elevation level of the sprinkler heads in the Factory Mutual tests[40] (ie., 18.3m elevation), compared to the class A foam tests conducted in this project (ie., 2.7m elevation). The effect of elevation on expansion ratio could not be examined in the test series due to physical limitations of the building in which the tests were conducted.

It was anticipated that further slight increases in the expansion ratio would have occurred as the pressure was increased beyond 85kPa. The limitation associated with the pump as detailed earlier may have had an affect on the results of the tests. In tests 1-4 the pump had the capacity to flow all four heads at the required pressure. In the case where only two or one head was operated the overall density associated with the discharge array would have been lower. In this situation the time required to fill the foam collector with foam would have been longer. With such a relatively low expansion foam, this additional time required to fill the foam collector would have given the existing foam more time to drain. Such an effect would have an impact on the 25% drain times and the expansion ratio results.

- **25% Drain Times**

In all of the tests the expanded foam exhibited fast drain times. Tests undertaken with the foam collector apparatus and pure water showed that 25% of the collector capacity could be drained in 15 seconds. Similar times were obtained for most of the foam tests conducted, hence the drain times can be categorised as being "instantaneous".

Tests undertaken by Factory Mutual Research Corporation with 3% AFFF and standard sprinklers obtained 25% drain times between 0.5-1.3 minutes (30-78 seconds).[40]

- **Distribution Tests**

Tests 1 and 2 achieved average densities of 8.3 l/min/m^2 and 8.2 l/min/m^2. These valves are in excess of the minimum average valve stipulated by UL Standard 199 (ie., 6.1 l/min/m^2). Tests conducted by Factory Mutual Research Corporation, with the same heads at the same flow rate with pure water, gave average density figures of 10.6 l/min/m^2, 11.81 l/min/m^2, 8.9 l/min/m^2 and 8.6 l/min/m^2 for four repetitive tests that were undertaken.[45]

UL Standard 199 also stipulates that all of the pans must achieve a minimum density of 75% of the required average valves.[32] This requirement equates to a density of 4.58 l/min/m^2 being obtained in all collection pans. In test number 1 this minimum valve was achieved in all trays. In test number 2 all but one of the trays (tray number 4) achieved this requirement. The density obtained in tray number 4 was slightly under the minimum valve (ie., 4.4 l/min/m^2).

The results show that there was considerable variation between the densities achieved in identical tray numbers for the two tests. Figure 6.3-1 shows this variation graphically. No logical explanation could be found for this variation. Tests conducted by Factory Mutual with pure water produced results with similar valves when repeated.[45] These results are shown in figure 6.3-2.

Figure 6.3-1: Density Variation for Tests 1 and 2.

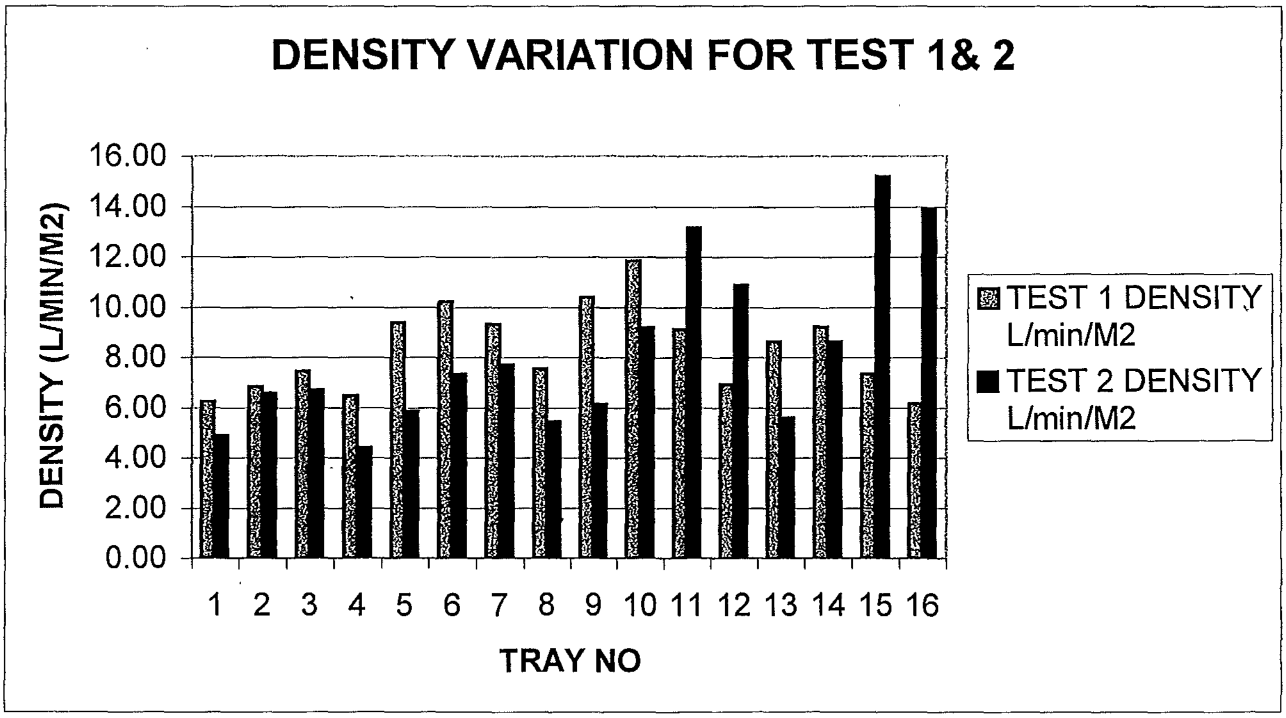
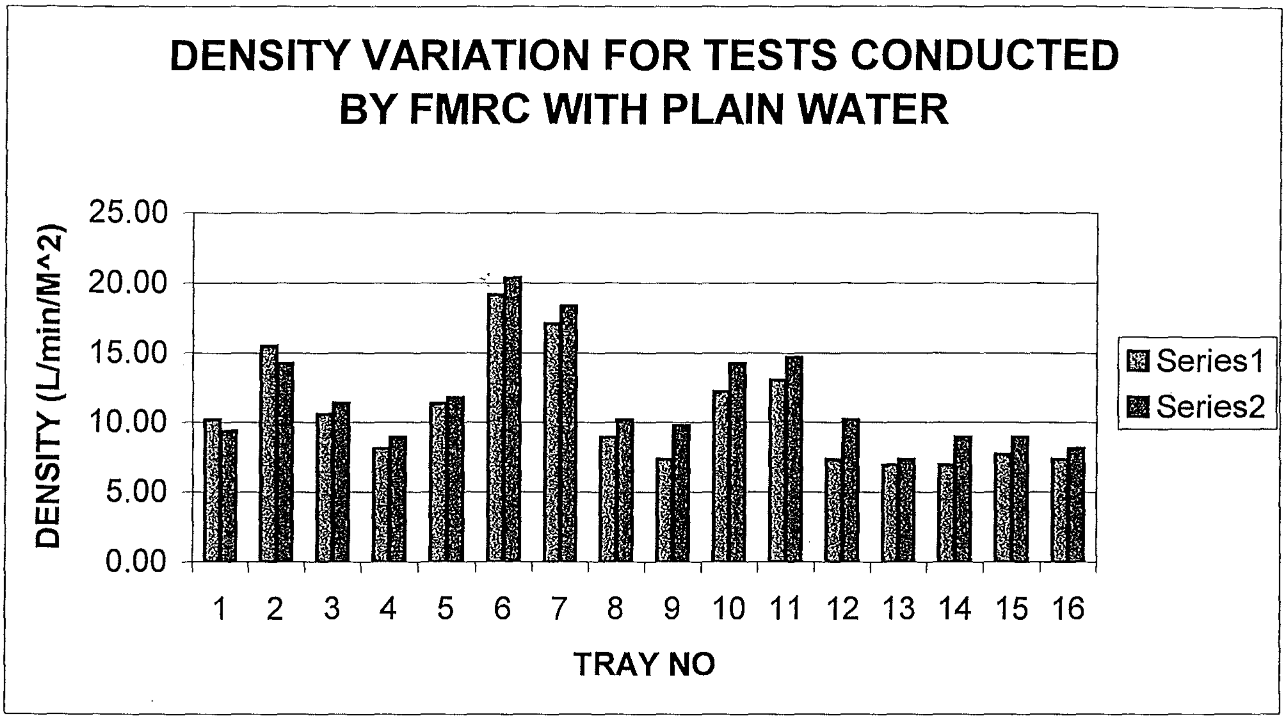


Figure 6.3-2: Density Variation for Tests Conducted by Factory Mutual with Plain Water.[45]



CHAPTER 7.0 ENVIRONMENTAL AND TOXICITY CONSIDERATIONS

7.1 Introduction

This chapter examines the potential environmental implications associated with a class A foam based sprinkler system. Increased global environmental concerns have seen more stringent requirements demanded by Governments and local environmental authorities. Standards and codes of practice are increasingly changing to incorporate environmental considerations.

In relation to fire protection practices environmental issues such as , "fire run off water" and foam systems have been given more attention. The 1998 edition of the NFPA Standard for Low Expansion Foam (NFPA - 11)[42] has incorporated a section on foam environmental issues. NFPA Standard 298,[46] has specific sections for the testing and acceptance of class A foams in relationship to; toxicity, biodegradability and fish toxicity. The USDA Forest Service as part of it's National Wildfire Suppression Technology Programme[47] has completed a comprehensive set of data relating to the environmental impact of several class A foams.

The discharge of foam solution from a class A foam sprinkler system into the environment could occur as a result of a genuine fire occurring. In this situation the associated "run off' water would be composed of class A foam solution and other contaminates associated with the nature of the fire and goods being protected. The discharge of foam solution to the environment would also eventuate as a result of mechanical damage or the failure of maintenance and service personnel to follow the correct isolation and test procedures. In a similar manner an environmental discharge of foam concentrate could occur during filling or servicing activities, or as a result of mechanical damage or failure of the associated concentrate storage tank and pipework.

7.2 Toxicity

The implementation of a class A foam sprinkler system could possibly result in personnel being in contact with foam concentrate or solution. In accordance with good health and safety practices it is prudent to identify and evaluate the potential hazards and establish guidelines or design practices which would see such hazards either eliminated or minimised. The resultant design safety features and procedures would have to meet the requirements of a number of interest groups such as; local health authorities, union or employee groups and fire service personnel.

The toxicity of several class A foams were examined as part of the USDA Forest Service National Wildfire Suppression Technology Programme.[47] These tests were undertaken in order to ensure that the use of class A foam did not result in increased risks to fire fighters, the general public or the environment. This programme required that foam manufacturers disclose all ingredients within their formula. Some manufacturers class A formulation did contain compounds that were classified as hazardous by the USDA Forest Service, the quantities were small hence the total risk was concluded to be insignificant.[47]

The USDA Forest Service study involved products being tested for acute oral and dermal toxicity and eye irritation. Acute oral and acute dermal toxicity were measured in terms of the medium lethal dose (LD_{50}). The (LD_{50}) is defined as the dosage, (in terms of milligrams of test material per kilogram of body weight) at which 50 percent of the test animals die. The tests were undertaken with laboratory rabbits.

NFPA - 298 lists the toxicity limits for class A foam concentrates and solutions.[46] These limits are the same as the USDA Forest Service requirements. NFPA - 298 also requires that foam concentrate shall be tested in accordance with "Pesticide Assessment Guidelines, Subdivision F, Hazard Evaluation: Human and Domestic Animals, US E.P.A. In Europe similar requirements exist. German foam agents have to undergo testing by the Hygiene Institute, Des Ruhrgebiets Gelsenkirchen.[48]

Personnel are most likely to be exposed to foam concentrate during the handling, transferring and testing of a class A foam sprinkler system. The USDA Forest Service report states that all of the concentrates tested caused moderate to severe irritation to the eyes and slightly to moderate skin irritation and chapping.[47] In order to minimise the risks to personnel, foam manufacturers recommend that appropriate protective safety clothing and goggles be worn when working with class A concentrate. The appendix of NFPA - 298 also recommends such practices.

Personnel or fire service crews could be exposed to class A foam solution from the over head sprinkler system as a result of a genuine fire or false activation resulting from mechanical damage to sprinkler heads or pipework. In this situation it is unlikely that personnel would be outfitted with appropriate safety equipment, hence the eyes and skin could be exposed to foam solution.

Appendix 2 lists a summary of the toxicity effects of various class A foam solutions formulated at 1%.

The results displayed in Appendix 2 show that all of the class A foam solutions tested by the USDA Forest Service comply with the established requirements. The primary irritation scores for skin irritation with the 1% solution ranged from 0.1 to 0.7 with an average score of 0.36. Based on these results the 1% class A solutions tested can be classified as having a "slightly irritating" effect on exposed skin. A slightly irritating effect is defined as having a primary irritation index between 0.1 - 0.9. Eye irritation results for the various solutions ranged between 2 - 10 in the case of "washed eyes". Based on these scores and the definitions listed, the effects of eye irritation can be categorised as being "minimally irritating".

The activation of a class A foam sprinkler system could result in personnel being exposed to foam solution. The abovementioned results indicate that any detrimental health effects would be minimum and within acceptable levels of personnel safety.

7.3 *Biodegradability*

The biodegradability of a foam solution can be defined as how "readily the chemicals in the foam are broken down by bacteria in the environment".[49] A number of methods exist for determining foam solution biodegradability.

In Germany foam solution biodegradability requirements have been based around tests concluded by the Hygiene Institute Des Ruhrgebiets Gelsenkirchen.[48] Whiteley has reported that the German standard may become a requirement for the rest of Europe.[49] These tests include COD (Chemical Oxygen Demand) and BOD (Biological Oxygen Demand).

The BOD test measures the amount of oxygen used by bacteria over a given period of time, as the chemicals in a foam solution are consumed as a food source. BOD tests are based around standard test duration's and can vary from five to twenty days. Twenty day tests are used if there is a lag phase in the bacterial population growth curve, which occurs as a result of the bacteria becoming acclimatised to the particular solution. The COD test is a measure of how much oxygen would be required to completely breakdown a unit quantity of foam solution to it's most oxidised state. With this method theoretical biodegradability is based on the ratio of BOD/COD.

Whiteley references the work undertaken by the Industrial Waste Laboratory of Wesleyan University, who concluded that a BOD/COD ratio above fifty percent is readily biodegradable.[49] A product with a BOD/COD ratio less than 15 percent is considered non biodegradable.[49] The German Standard requires a BOD/COD ratio of seventy percent. De Vries reports that only one class A foam product (Silvex - G) is approved in Germany to date.[48]

The USDA Forest Service have undertaken foam biodegradability tests on class A foam using both "aerobic aquatic" and "ready" biodegradability methods. The National Fire Protection NFPA Standard - 298 is based on "aquatic" biodegradability. This standard requires that aerobic aquatic biodegradation tests be tested in accordance with CFR 40 part 796.3100.[46] The test determines if the foam solution is biodegradable in natural aerobic freshwater environments.

The degree of biodegradation is determined by the measurement of carbon dioxide formed from a test sample in a certain period.

"Ready" biodegradability tests are based on Organisation for Economic Co-operation and Developments guidelines for testing chemicals.[47] This test involves the inoculation of the bacteria medium to be tested. The test method does not include a acclimatization period. The degree of biodegradation is determined by the decrease in oxygen content over a twenty eight day period.[50]

It is feasible that a discharge from a class A foam system would have to be treated by a sewerage treatment plant or similar industrial facility. The operators of these plants would be interested as to what effects class A foam solutions would have on the bacterial cultures present in their plants. The results of the aquatic biodegradability tests would indicate contamination tolerance levels.

Appendix 2 lists a summary of the aerobic aquatic biodegradability tests for several class A foam solutions. These results show that only one foam product was readily biodegradable while another was only partially biodegradable. The USDA Forest Service report states that these results were not consistent with those undertaken independently by the foam suppliers using the same methods, hence the authors recommended further tests.[50] The German organisation, Hygiene Institute des Ruhrgebiets, conclude that the only class A foam product approved to date is expected to have "no negative impacts on the biological section of a waste water treatment facility".[48]

The USDA Forest Service "ready" biodegradability tests show that all but two of the products tested can be classified as being "readily biodegradable". These results are also displayed in Appendix 2.

7.4 Fish Toxicity

The discharge of class A foam solution from a sprinkler system could flow through storm water drains or via other avenues to potentially endanger the aquatic environment and fish species present.

The potential danger of class A foam solutions endangering fish species during wildland and forest fire fighting has resulted in toxicity studies being undertaken. The US Fish and Wildlife Service conducted a series of tests which examined the toxicity of class A foams and other forest fighting mediums on several aquatic organisms. These tests included green algae, rainbow trout, flathead minnows and chinook salmon.

The tests were performed in accordance with ASTM method E-729-88a (standard guide for conducting acute toxicity tests with fishes, macroinvertebrates and amphibians (ASTM 1989).

The tests found that within a species some life stages were more sensitive to a foam solution than at other stages of development. Rainbow trout in a 60 day post hatch stage were selected as a "bench mark" for other species, as they were found to be more sensitive than most species.[50]

Fish toxicity is measured in terms of lethal concentration to 50 percent of the population over a 96 hour period (96 Hr LC_{50}). Measurements are made in milligrams per litre which is equivalent to parts per million (ppm).

Appendix 2 lists the results of the tests performed by the US National Biological Service, on rainbow trout at various life stages with several class A foams.

These results show that all of the products tested achieved the required aquatic toxicity level of LC_{50} > / 10 mg/litre of ASTM soft water after a 96 hour period.

The NFPA Standard 298 requires that fish toxicity tests should also be conducted using rainbow trout, but tested in accordance with "Environmental Protection Series Biological Test Method: Acute Lethality Test using Rainbow Trout", report EPS1/RM/9.[46] These tests are similar to those undertaken by the US National Biological Service.

Testing has found that the discharge of some class A foams into natural water resources can result in the mortality of aquatic invertebrates.

Such organisms rely on water surface tension being present in their aquatic environment for mobility.[50] Some Class A foams have a detrimental effect on aquatic invertebrate populations by reducing the water surface tension.

The report published by the US National Biological Service concludes that "toxicity values suggest that accidental entry of fire fighting chemicals into aquatic environments could adversely effect fish populations".[50]

7.5 Conclusion - Environmental Implications

To date no (known) scientific study has specifically examined the likely environmental impact associated with the discharge of foam solution from a class A foam sprinkler system. The 1998 edition of the NFPA Standard 11 specifically addresses environmental considerations when using fire fighting foam.[42] This standard recommends procedures for the collection, treatment and disposal of foam solution following a discharge, in order to avoid adverse environmental damage. These recommendations specifically relate to the use of class B type foams.

In general, class B type foams contain greater potential to damage the environment than class A type foams. Class B type foams are typically applied at a concentration of 3%, while potential class A foam systems proportioning ratio would be in the order of 0.5-1%. Synthetic type class B concentrates such as AFFF contain flurochemical surfactants which are not readily biodegradable.[51] Class A foams typically do not contain flurochemical surfactants.[48] Protein based class B foams have also been reported as being potentially environmentally damaging as they have a high ammonia nitrogen content and can cause nutrient loading, hence when discharged in a treatment facility, can lead to "organic overload".[49]

The quantity of foam solution discharged from a foam water sprinkler system will be dependent on the number of heads that operate, the sprinkler orifice size, system pressure, and the time it takes fire service personnel to shut down the main sprinkler isolation valve. Statistics relating to fires in sprinkler protected buildings give records of the number of heads operated and details of the building use. Marryatt reports that 95.24% of all fires occurring in sprinkler protected buildings are controlled in New Zealand and Australia by eight heads or less.[52] The same quantity of heads control 87.4% of all fires in the USA.[52]

With only a small number of heads operating, the pressure applied to the heads will be much higher than the minimum pressure required by the applicable sprinkler standard.

It follows that the unit flow rate per head will be higher, as the unit sprinkler flow is proportional to the square root of the head pressure. The actual pressure on the heads will be a function of the water supply available and the characteristics of the pipework array.

Table 7.5-1 lists the estimated amount of foam solution likely to be discharged from eight sprinkler heads with 15mm orifice for various head pressures.

Table 7.5-1: Estimates of the quantity of Class A foam discharged from a sprinkler system, based on eight heads operating.

Average Head Pressure P (kPa)	Estimated Solution Flow Rate Q (l/min)	Estimated Solution Discharged			Estimated Concentrate Discharged		
		10 mins (litres)	20 mins (litres)	30 mins (litres)	10 mins (litres)	20 mins (litres	30 mins (litres)
100	640	6,400	12,800	19,200	32	64	96
150	784	7,840	15,680	23,520	39	78	118
200	905	9,050	18,100	27,150	45	91	136
250	1,012	10,120	20,240	30,360	51	101	152
300	1,109	11,090	22,180	33,270	55	111	166

Notes

1) *Solution flow rates have been estimated from eight heads, flowing at the various head pressures and $Q = K\sqrt{P}$, where $K = 8.0$, ie., for a sprinkler with 15mm nominal orifice.*

2) *Concentrate quantities are based on proportioning at 0.5%.*

Table 7.5-1 above has been based on the historical success in controlling fires with sprinkler systems. Table 7.5-2 estimates solution discharge rates based on typical sprinkler design parameters.

Table 7.5-2: Estimates of the quantity of Class A foam discharged from a sprinkler system based on typical sprinkler system design parameters.

Assumed Density and Area of Operation ($l/min/m^2$, m^2)	Estimated Solution Flow Rate Q (l/min)	Estimated Solution Discharged			Estimated Concentrate Discharged (at 0.5%)		
		10 mins (litres)	20 mins (litres)	30 mins (litres)	10 mins (litres)	20 mins (litres	30 mins (litres)
7.33; 232 (1	1,700	17,000	34,000	51,000	85	170	255
13.85; 371 (2	5,138	51,380	102,760	154,140	257	514	771
20; 300 (3	6,000	60,000	120,000	180,000	300	600	900

Notes:
1) NFPA-13 OH2 density/area method.
2) NFPA-13 EH2 density/area method.
3) NZS4541 Category 3, block stacked to 5.7m high.

Tables 7.5-1 and 7.5-2 above provide two approaches to the likely amount of foam solution discharged from a Class A foam water sprinkler system.

As previously mentioned the environmental section contained in Appendix E of NFPA Standard 11, specifically relates to Class B foams. Many Class B foam systems protecting flammable goods warehouses or process risks are deluge systems, hence the flow rate and quantity of solution discharged is likely to be higher than that of a closed head sprinkler system.

If the successful testing of Class A foam systems enables a density reduction compared to a water based system, the quantity of contaminated fire run-off water would be reduced. In this situation the installation of Class A foam sprinkler technology could potentially reduce environmental damage.

de Vries suggests that the toxicity of fire ground run-off water is more a function of the toxicity of the goods involved in the fire as opposed to the extinguishing agent applied.[48] de Vries assumption has been based on the work of Wieneke,[53] who collected 54 samples of fire ground run-off water, presumably from fires fought by manual means. Wieneke also undertook tests on a series of identical fires where the toxicity of the run-off water was evaluated for both Class A foam and plain water extinguishing agents. Table 7.5-3 shows a summary of these results.

Table 7.5-3: Toxicity characteristics of fire ground run-off water and Class A foam solution.[48]

Extinguishing Medium	Conductivity (ms)	C.O.D. (mg/L)	S.A.C. 254nm	Dilution for 10% Inhibition	pH
*Mean of 54 real fire samples	6,574	7,171	904	1,637	8
Results of identical fire tests					
- Plan water mean	524	198	84	5.5	7.5
- 0.5 Class A foam mean	917	2,319	229	1,180	9.6

(Source - adapted from[48])

As outlined in Section 7.3 above, the tests conducted by Hygiene-Institute des Ruhrgebiets Gelsenkinchen in Germany concluded that certain foam manufacturers products are readily biodegradable.[48] In contrast to this, the USA Forest Service recommended further tests as only one product was found to have acceptable results based on aerobic aquatic test methods, while all but two products had acceptable biodegradability levels, based on the "readily biodegradability test method".[47] The results of fish toxicity tests described in the previous section highlight the need to avoid discharges of foam solution into natural waterways.

The design process of a Class A foam water sprinkler system should incorporate expected flow rate calculations. Local fire service crews should be consulted in order to assess their response time and the likely period before the sprinkler isolation valve would be closed. This information will give the engineer an estimate of the likely quantity of foam discharged.

The following information should be presented to the local environmental authorities and the operators of waste treatment plants;

- Details on the proposed concentration, including biodegradability, toxicity and fish toxicity valves.
- Estimated quantity of solution to be discharged.
- Estimated flow rates.
- Proposed method of disposal.
- Proposed method of preventing environmental damage.

The abovementioned organisations may require an engineered containment system. Such a system would contain the discharged foam solution, where it could later be either forwarded to a waste treatment facility at a prescribed rate or discharged to the environment after pre-treatment. NFPA-11 gives further guidance on such systems. The existence of "event initiated procedures" may be adequate for the local environmental authorities requirements in lieu of a fixed containment system. Such procedures may include either the automatic or mechanical closing of valves associated with storm water or sewerage disposal.

CHAPTER 8.0 SYSTEM HARDWARE AND MATERIAL COMPATIBILITY

8.1 Introduction

Foam solution has been applied successfully to sprinkler systems protecting flammable goods warehouses for the last two decades. Recognised standards such as the 1994 edition of NFPA Chapter 16A (Installation of Closed Head Foam Water Sprinkler Systems)[1] has evolved out of previous editions and the findings of large scale fire tests. Suitable foam hardware for the purposes of storage, transferring and proportioning is available with independent third party approval.

The engineering hardware arrangement of a foam water sprinkler system must take into account many factors such as; testing requirements, material compatibility, environmental considerations and ambient temperature extremes.

In an actual fire situation the flow rate of the system will be dependent on the number of sprinkler heads that operate and the individual characteristics of these heads. The design flow rate will be established from a chosen area of operation and the selected foam - water density. To account for the range of possible flow rates within the design parameters it is advantageous to have a balanced proportioned system.

A balanced proportioned system is engineered so that the proportioning rate will stay relatively constant, regardless of changes in flow demands or the foam concentrate or water supply pressure. For foam water sprinkler systems balanced proportioning is usually achieved by using either a "balanced pressure pump" arrangement or a "bladder tank" an associated hardware. Section 8.2 and 8.3 outline typical hardware arrangements for these two methods.

8.2 Bladder Tank Balanced Proportioning

Activation of the abovementioned system occurs when sprinkler heads (9) within the protected area are activated by heat from a fire. The flow of water within the system will cause the alarm (4) valve seat (or clapper) to lift.

When the aforementioned action occurs water will flow through the water motor alarm (18) gong line. Based on the valve arrangement detailed in figure 8.2-1 this action will operate the alarm valve and supply water pressure to the actuation port of the piston operated valves (11 & 12), thus opening the valves. The opening of the piston operated valve causes pressure to be supplied to the elastomeric membrane of the bladder tank (10) through the inlet supply line.

The pressure applied to the internal elastomeric bladder "squeezes" the foam concentrate stored within, thus providing a supply of foam concentrate, through the open piston operated concentrate control valve (12) to the inlet of the proportioner (5). The concentrate inlet side of the proportioner contains a metering orifice (6) which is engineered to suit the desired foam solution proportioning ratio. Water from the sprinkler system is mixed with concentrate in the low pressure area of the proportioner to form a foam solution in the pressure recovery area.

It is possible to have a functioning system and omit the piston operated valve (11) on the water supply line. With this reduced valve arrangement the bladder would be constantly subjected to the nominal pressure of the sprinkler system. The choice of valving arrangement will depend on factors such as the requirements of the authority having jurisdiction and the sprinkler control valve configuration. The omission of a piston operated valve from the water supply line is most suited to a "floating type" sprinkler valve arrangement where a restricting flow orifice and retardation chamber are utilised to overcome surges in the water supply. A sprinkler system which is configured with a "standing pressure" downstream of the alarm valve, higher than the available static supply pressure (ie., a super pressurised system), may require a piston operated valve on the water supply line if the standing pressure is excessive in relation to the working pressure of the elastomeric bladder.

The schematic arrangement Figure 8.2-1 shows additional devices that are required for a functional system and to permit regular testing.

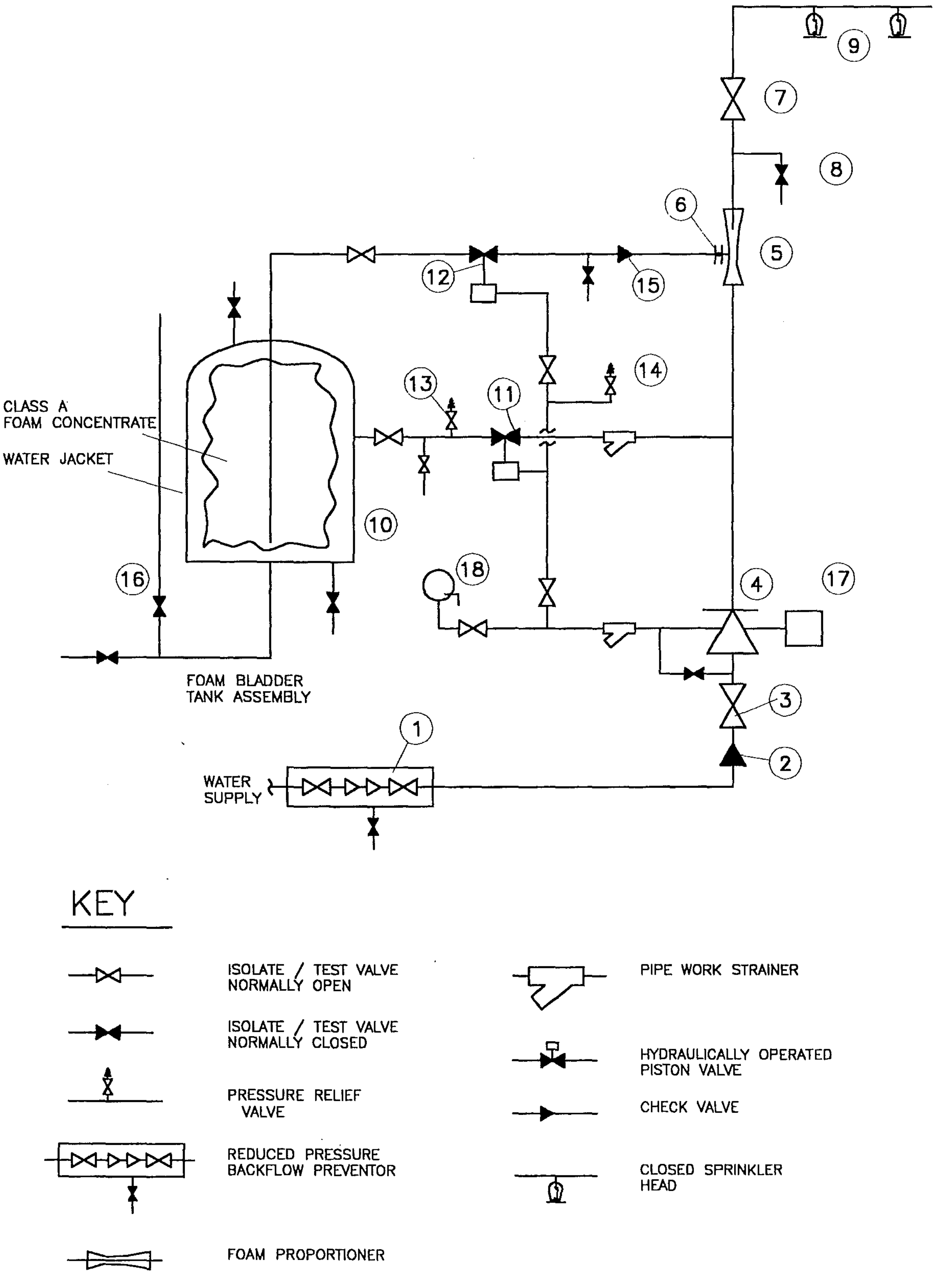
A reduced pressure type back flow preventor (1) is usually required by the water supply authority to prevent possible contamination of the towns water supply. A pressure relief (13) valve may be fitted to the water supply line to protect the elastomeric bladder from water supply pressures in excess of the safe working pressure.

In a similar manner the piston operated control valve may require a pressure reducing valve (14) to be installed on the upstream side. The installation of a check valve (15) on the foam concentrate line will ensure that water does not contaminate or dilute the foam concentrate supply. The system will require an alarm signalling, and transmitting device (17) if automatic intervention is required from the local fire service.

Good fire engineering design of the valving arrangement will facilitate regular testing of the system to ensure that components remain functional. The bladder tank can be fitted with a sight glass (16) to allow checks on the foam concentrate level. Testing valves can be installed to enable the piston operated valves to be regularly operated. An isolate valve (7) and inspection cock (8) may be required to be installed, by the authority having jurisdiction, down stream of the proportioner to enable testing or sampling of the solution. All valves should be locked in their "normal" operating position.

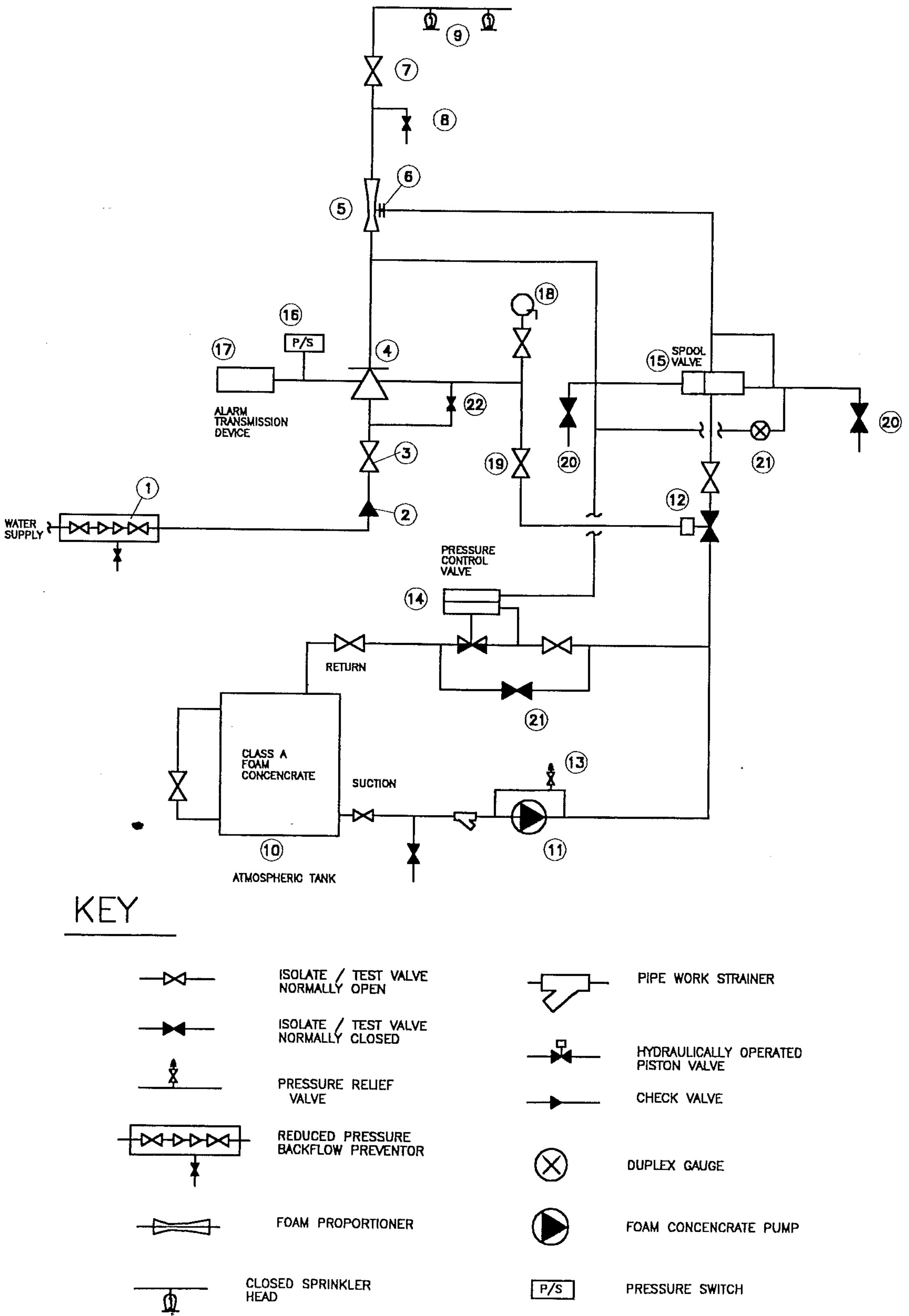
In addition, valves of critical importance to the system operation should be "supervised", hence any interference with a valve will send a signal through to the monitoring station via the main fire alarm panel or the sprinkler system alarm transmission device.

Figure 8.2-1: Typical schematic of hardware arrangement for class A sprinkler system, utilising a bladder tank for foam concentrate storage.



8.3 Balanced Pump Proportioning

Figure 8.3-1: Typical schematic for balanced proportioning with a pumped concentrate supply and in-line pressure proportioner.



Balanced pressure proportioning for a foam water sprinkler system can also be achieved by utilising a hardware arrangement as detailed above. With this configuration the foam concentrate is stored within an atmospheric tank (10). The system will be activated by a drop in pressure within the sprinkler system as a result of sprinkler heads (9) operating. The alarm valve clapper (4) will lift and water will flow through the water motor gong (18) line. This action will see the gong operate and cause the piston operated hydraulic valve (12), installed on the concentrate line, to open. A pressure switch (16) located on the down stream side of the sprinkler alarm valve will relay a signal to the foam pump (11) controller, hence causing the pump to start.

Pressurised foam concentrate will flow through the concentrate supply line. A pressure control valve (14) installed on the concentrate return line, senses both the concentrate supply pressure and the water supply pressure and regulates the concentrate supply to a higher pressure that the water supply. This valve by-passes surplus concentrate back to the atmospheric storage tank.

A spool type valve (15) senses the concentrate and water supply pressures entering the proportioner. This device regulates the higher concentrate supply pressure to ensure that both mediums enter the proportioner with equal pressure. The spool valve arrangement enables a rapid response to system pressure fluctuations and ensures accurate proportioning of the concentrate. The proportioner (5) contains a metering orifice, low pressure area and recovery area as described in Section 8.2 above.

Additional valves are necessary to facilitate testing and functional requirements. A pressure relief valve (13) and associated by-pass is utilised to protect the pump casing and system components. Provision is made for the testing of the pump through the pump test return line (21). Additional provision can be made for testing the operation of the piston operated valve and gong line by utilising test valve (22). The system hardware configuration may also incorporate a provision for flushing, valves (20).

8.4 Material Compatibility and Corrosion

This section first examines the causes of deterioration and corrosion with a standard wet pipe sprinkler system. Commonly used sprinkler materials are evaluated for the suitability with class A foam.

Post installation investigations of standard wet pipe sprinkler systems have concluded that the main causes of steel pipework internal deterioration are; oxygen availability, presence of sediment or debris and galvanic couples.[54]

Recent findings by the National Fire Sprinkler Association (NFSA)[55] have concluded that microbiologically influenced corrosion is a major problem for sprinkler systems.

The amount of oxygen available to a wet pipe sprinkler system will depend on the frequency in which the static sprinkler water is drained and replaced with fresh water, containing oxygen. The fresh oxygen introduced to the sprinkler system will initially deteriorate or corrode the steel pipe wall through an oxidation process. The oxidation process is terminated when the available oxygen within the system has been consumed. The initial build up of scale or corrosion forms a protective layer which slows the rate at which further corrosion occurs.[54]

Bsharat[55] concluded, that most carbon steel sprinkler systems have an environment that is well suited for microbiologically influenced corrosion to occur. Typical characteristics of "microbiologically influenced corrosion" include, pinhole leaks with dark brown or rust coloured slime on the interior of the piping. Microbiologically influenced corrosion can occur as a result of either anaerobic or aerobic bacteria being present in the sprinkler system. The stagnant water within a sprinkler system will eventually de-oxygenate. This provides a perfect environment for anaerobic bacteria. Aerobic bacteria is likely to occur with a sprinkler system where the water is changed frequently. In this situation fresh air, microbes and nutrients make it possible for the aerobic bacteria to grow.[55]

The amount of sediment within a sprinkler pipework array is a function of the quality of the water supply available and the nature of the inline strainers. Sedimentary build up can result in additional friction losses within the pipework array, hence pressure losses will be increased.

Galvanic corrosion occurs as a result of two dissimilar metals being in contact with each other. This situation can be avoided by utilising materials that are compatible with one another or by separating the materials with a neutral or passive boundary.

At present there exists no comprehensive (known) independent third party publication specifically relating to the compatibility of materials found in a closed head sprinkler system with class A foam solution. The US Forest Service as part of it's "National Wildfire Suppression Technology Programme" undertook investigations into the effects of corrosion between several metals exposed to both class A foam solution and concentrate[47]. The metals and alloys selected were based on materials generally found in forest fire appliances such as fixed-wing air tankers, helicopter buckets and ground engines. The materials tested were; 2024-T3 aluminum, 4130 steel, yellow brass and AZ31B magnesium. Tests were conducted at two different temperatures, with specimens totally immersed and partially immersed. Several class A foam concentrates were tested. Tables 8.4-1 and 8.4-2 list a summary of the results of the tests for both 4130 steel and yellow brass. The results of AZ31B magnesium, and 2024-T aluminum have not been included in these tables as these materials are not commonly used in sprinkler systems. Although tests were conducted at both 21 Deg. C and 49 Deg. C, only the results of the 21 Deg. C tests are shown in tables 8.4-1 and 8.4-2, as such a temperature is more appropriate to sprinkler systems.

Table 8.4-1: Uniform Corrosion Rates for Steel and Brass with Fresh Concentrate.[47]

Foam Product (Fresh Concentrate)	Steel 4130 Totally Immersed 21 Deg. C mm/Year	Steel 4130 Partially Immersed 21 Deg. C mm/Year	Yellow Brass Totally Immersed 21 Deg. C mm/Year	Yellow Brass Partially Immersed 21 Deg. C mm/Year
Angus ForExpan	0.0010	0.0038	0.0005	0.0008
Ansul Filv-ex	0.0249	0.0330	0.0432	0.0432
Fire Quench	0.0069	0.0163	0.0053	0.0033
Fire-Trol FireFoam 103	0.0305	0.0330	0.0003	0.0003
Fire-Trol FireFoam 104	0.0279	0.0234	0.0104	0.0239
Phos-Chek WD 881	0.0330	0.0305	0.0003	0.0020
Phos-Chek WD 861	0.0168	0.0198	0.0074	0.0061
Pyrocap B-136	0.0193	0.0069	0.0018	0.0061
Average	**0.0200**	**0.0208**	**0.0086**	**0.0107**

Table 8.4-2: Uniform Corrosion Rates for Steel and Brass with 1% Foam Solution.[47]

Foam Product (1% Solution)	Steel 4130 Totally Immersed 21 Deg. C mm/Year	Steel 4130 Partially Immersed 21 Deg. C mm/Year	Yellow Brass Totally Immersed 21 Deg. C mm/Year	Yellow Brass Partially Immersed 21 Deg. C mm/Year
Angus ForExpan	0.0036	0.0137	0.0008	0.0010
Ansul Silv-ex	0.0079	0.0221	0.0003	0.0015
Fire Quench	0.0239	0.0236	0.0003	0.0005
Fire-Trol FireFoam 103	0.0249	0.0251	0.0003	0.0005
Fire-Trol FireFoam 104	0.0061	0.0147	0.0056	0.0038
Phos-Chek WD 861	0.0081	0.0155	0.0097	0.0053
Phos-Chek WD 881	00.191	0.0188	0.0008	0.0008
Pyrocap B-136	00.130	0.0065	0.0010	0.0008
Average	**0.0133**	**0.0188**	**0.0023**	**0.0018**

Note - Corrosion rates determined by 90 day weight loss tests.

The National Wildfire Suppression Programme concluded that all of the results were within the acceptable limits of 0.0508mm to 0.127mm. The maximum corrosion rates varied for the various fire fighting hardware devices.[47] The programme also references a previous study undertaken by "Canadair" on the compatibility of class A foam with several non-metallic materials, such as nitrile rubber, cross linked polyethylene/nylon, PVC and fibreglass with epoxy resin.[47] The report demonstrated that some materials showed changes in hardness or volume following exposure to the foam. The hardness changes associated with certain materials were within the Canadair limits, however, not all of the volume changes complied with the minimum standard required. The authors of the National Wildfire Suppression Programme report concluded that further testing, and a review of the Canadair test methods, is needed.[47]

NFPA-16A states that foam water sprinkler systems should be pre-primed with a foam solution[1]. Pre charging the system ensures that foam solution can be immediately discharged from the sprinkler heads. If the system was discharged with water only there would be a time lag until solution would be applied to the fire. During this time lag stage the fire could continue to develop.

The precharging of a class A foam water system may have an effect on the corrosion rates of the system, hence an analysis needs to be conducted to ensure material compatibility.

Tables 8.4-3 and 8.4-4 list the various components of a class A foam - water sprinkler system and details typical materials that are used in there construction. Table 8.4-3 specifically relates to components subject to solution, while table 8.4-4 lists components subjected to class A foam concentrate. These tables have been based on corrosion and compatibility information sourced from Ansul Incorporated (relating to Silv-ex) and the results of the National Wildfire Suppression Technology programme.[47] As such, the aforementioned tables do not provide an overall compatibility statement for all class A foams.

In specifying a class A foam sprinkler system, the engineer shall ensure that the individual components of the system are compatible with the foam selected. Until further testing is conducted, materials used will be restricted to proven compatible materials such as; black steel, brass, stainless steel and certain non-metallic compounds. Further tests are needed to evaluate if class A foam systems will be effected by microbiologically influenced corrosion.

Table 8.4-3: Typical Materials Exposed to Foam Concentrate in a Class A Foam System.

Component	Typical Material Used	Compatibility Yes/No/Unknown
Storage Tank	• Plastic (PVC) • Stainless Steel • Mild Steel • Galvanised Steel	Yes[56] Yes[56] Yes[47] No[56]
General Isolate Valves, Check Valves, Relief Valves, Pressure Control Valves	• Cast Iron • Black Steel • Stainless Steel • Yellow Brass	Unknown[56] Yes[47, 56] Yes[56] Yes[47, 56]
Bladder Tank	• Buna-N with Nylon Reinforcement	Unknown[56]
Proportioner	• Brass	Yes[47]

Table 8.4-4: Typical Materials Exposed to Foam Solution in a Class A Foam Sprinkler System.

Component	Typical Material Used	Compatibility Yes/No/Unknown
Alarm Valve	• Body Cast Iron (ASTM A48) • Ring Seat-Bronze (ASTM B62) • Clapper facing - EPDM Rubber	Unknown[56] Unknown[56] Yes[56]
Roll Groove Coupling	• EPDM	Yes[56]
Sprinkler Head	• Body-Bronze (ASTM B176) • Bulb Retainer-Phospher Bronze (ASTM B103) • Gasket Spring Plate (Beryllium Nickel) • Deflector-Brass	Unknown[56] Unknown[56] Unknown[47, 56]

Steel Pipe	• Schedual 40 (ANSI/ASTM A53)
	  • Black
	  • Galvanised
	• British Standard BS1387 Medium Grade
	  • Black
	  • Galvanised
		
		Yes[47]
		Unknown[56]
		
		Yes[47]
		Unknown[56]

Pipe Fittings (Roll Groove/ Screwed Fittings)	• Cast Malleable Iron
	  • Black finish
	  • Galvanised finish
		
		Yes[47]
		Unknown[56]

Isolate and Test Valves (large bore)	• Body-Cast Malleable Iron • Gate/Ball - Stainless • Stem - Brass	Unknown[56] Yes[56] Yes[56]
Jointing Compounds	• PTFE type	Yes[56]

CHAPTER 9.0 POTENTIAL APPLICATIONS

9.1 Introduction

This chapter examines the potential applications of a class A foam based sprinkler system.

The implementation of a class A foam based sprinkler system would be dependent on sound scientific fire tests being undertaken with favourable results. Section 10.2 of this report discusses the requirements for further testing and suggests typical methology that should be employed.

To justify the installation of a class A foam based sprinkler system, such technology would have to offer advantages over a standard sprinkler system. The potential benefits of applying class A foam solution to sprinkler systems could arise as a result of a number of factors. Typical gains could be of the following form;

- Cost Benefits
- Improved Fire Suppression Performance
- Environmental advantages

Cost benefits could arise as a result of reduced density requirements. Reduced density requirements would lead to savings in labour, materials and water supply requirements.

The outcome of sound scientific tests would ultimately determine the suppression performance, limitations and possible applications of this technology. The manufacturers of class A foam concentrate state that the extinguishing agent can be applied to a range of class A commodities such as; wood, paper, coal and rubber.[4] The following sections consider the potential applications of these commodities.

9.2 Plastic Commodities

As previously mentioned, the NFPA Research Foundation had planned to undertake a study into class A foam based sprinkler systems.[3] This project was cancelled due to sponsorship being withdrawn.

Initial NFPA Research Foundation discussions envisaged that the technology should be investigated as a potential solution in protecting extreme hazard scenarios, eg., plastic racked storage applications.[2]

Section 2.3 of this document details the results of fire tests undertaken with polypropylene boxes rack stored and protected with a class A foam based sprinkler system. This combination proved more effective in terms of minimising fire damage and using less extinguishing agent compared to plain water.[8, 9] Similar results were obtained by Takahaski[23] (refer section 2.7), who demonstrated that dilute concentrations of AFFF solution were more effective on an array of commonly used plastics than plain water.

In contrast to these results, tests undertaken by NIST on cribs constructed out of pine and plastic sticks (as described in section 2.6), revealed no significant differences to the rate of heat release reduction rates when applied with either water or class A foam solution.[22] It should be noted that with both the tests undertaken by Takahaski and NIST, extinguishing agents were not applied through sprinkler system hardware.

Mass retention tests performed on vertical vinyl panels showed that water performed better than class A foam solution.[20] This characteristic maybe an advantage or disadvantage, depending on the orientation of the material being protected and the location of the origin of the fire. In the case of a fire originating at the bottom of a vertical plastic storage array, protected by overhead sprinklers, the rapid "run-off" (at high level) would assist in distributing extinguishing agent to the seat of the fire. If the origin of the fire was at high level the application of class A foam could have detrimental effects.

The results of the tests mentioned above do indicate that further testing to evaluate the effectiveness of class A foam based sprinkler systems is warranted. Possible applications as a result of successful testing could include the following;

- Racked plastic storage arrays.
- Stored plastic pallets.
- Plastic manufacturing and process industries (ie., storage protection).
- Retail outlets, specialising in plastic goods (eg., toys, household commodities, etc).

9.3 Paper Products and Storage

A fundamental characteristic of class A foam solution is its reduced surface tension properties, compared to water. In the protection of paper products this could be an advantage. The applied extinguishing agent would penetrate deeper into the surface and provide increased surface area coverage as demonstrated by Josler with tests on wood panels.[20]

The storage of paper can constitute a high fire fuel load when block stacked rolls are stored end on end or on side.[57] The storage of roll paper is common in the papermaking, newspaper and printing industries. A number of serious, high loss fires have occurred with this commodity.[57,58] Factory Mutual Research Corporation's fire records show that 458 roll paper storage fires occurred in the 28 year period, 1962-1989.[57]

In brief, these fires constitute a severe hazard. The high storage configurations and the close distance between adjacent arrays forms a series of natural chimneys, or flues, for fire to develop within. This arrangement makes it difficult for sprinkler systems to distribute water to all areas.[59] A significant characteristic of these fires is the rapid initial fire spread across the surface of the rolls.[57] Fire tests have shown that ceiling temperatures can rapidly develop to critical levels.[60]

NFPA standard 231F specifically addresses sprinkler systems for roll paper storage configurations.[59] The protection recommendations made in this prescriptive code have largely been based on full scale fire tests, with some extrapolation for extreme hazard scenarios.[57,60] Recent tests have shown that large drop sprinkler heads are more effective than large orifice heads.[57]

Tests have shown that the grade (weight per unit area) of paper is an important consideration in evaluating the fire risk. In brief, as the paper weight is reduced the fire hazard is increased, hence tissue paper constitutes more of a risk than newsprint.[57] Factory Mutual Research Corporation test results have shown that paper texture is also important. A paper product with an absorbent or fibrous texture will have a higher flame spread rate and will absorb more water.[57]

Factory Mutual comment that the high absorption rates of tissue type products makes them more difficult to extinguish in certain orientations.[57] In the case where a high pile tissue paper storage array is protected by overhead sprinklers, and a fire originates at low level, most of the water will be absorbed by the storage array as opposed to running down the array to the seat of the fire.[57] This situation would result in continued fire development. The above situation indicates that the addition of class A foam solution would have further detrimental effects, as its reduced surface tension properties would contribute to even deeper penetration in a localised area.

The addition of class A foam could prove to be beneficial to rolled stored paper arrays, with heavy and medium grade densities. Many individual paper rolls are wrapped with either a heavy weight grade of paper or plastic wrapping.[57] Specific fire tests would have to be performed on individual paper grades and storage configurations, to ascertain if the addition of class A foam would have any advantages over plain water as a suppression agent.

9.4 Limited Water Supply Situations

Tests undertaken by Underwriters Laboratories (as detailed in section 2.2), concluded that the quantity of extinguishing agent needed to control a residential fuel package with a sprinkler system, could be halved if 0.3% class A foam solution was used as opposed to pure water.[7] The successful outcome of these tests solved a specific problem relating to a limited extinguishing agent storage capacity. This technology could be extended to other risks where a sufficient water supply is not available.

Possible applications include the following;

- Private dwelling and other residential installation with marginal water supplies.
- Commercial and industrial facilities predominantly housing class A goods with marginal water supplies.

In practice, economic and environmental factors would also need to be confirmed in order to establish if the technology was providing an overall advantage. If water supplies are marginal it maybe more cost effective to install a booster pump and or a water storage tank, as opposed to the inclusion of class A sprinkler hardware.

9.5 Warehousing of Stored Rubber Tyres

A number of major fires have occurred in tyre storage facilities. In Hagersville, Canada, in February of 1990, a fire occurred in an outside tyre storage facility as a result of arson. The fire took 17 days to control and caused major environmental damage.[61]

Automobile tyres are typically manufactured from styrene-butadiene rubber. This compound is a synthetic rubber built up from copolymerized synthetic monomers of butadiene and styrene.[62] The gross heat of combustion of rubber automobile tyres is approximately 32.6 MJ/kg.[63] Researchers have reported the average mass of an automobile tyre to be 8.3 kg,[64] hence the storage of a large number of tyres with such a high heat of combustion would constitute a significant fire energy load. Typically a stored array of tyres will produce a fire with a rapid growth and high temperatures.[65] Such fires are typically deep seated. Their individual shape and configuration within a storage array tends to lead to shielded fires.[64] If sufficient oxygen is available the size of the fire will only be limited by the quantity of fuel (amount of tyres) present, hence such fires can be categorised as "fuel limited". Experimental work has shown that tyres have auto-ignition temperatures in the range of 200^0C to 428^0C.[66]

The National Fire Protection Association has published a specific standard (NFPA 231D) to address the unique risk of protecting stored rubber tyres.[65] This standard has a section which specifically addresses stored tyres housed in a spinklered building. This prescriptive standard details application density requirements which vary with storage configuration, tyre orientation and height. The standard permits the use of high expansion foam as a means of reducing the overhead sprinkler density. In the case of extreme storage hazard configurations both high expansion foam and listed overhead sprinkler densities are required.[65] The latest edition of this standard (1994) incorporates the findings of a full scale fire test undertaken by the Factory Mutual Research Corporation.[65, 67]

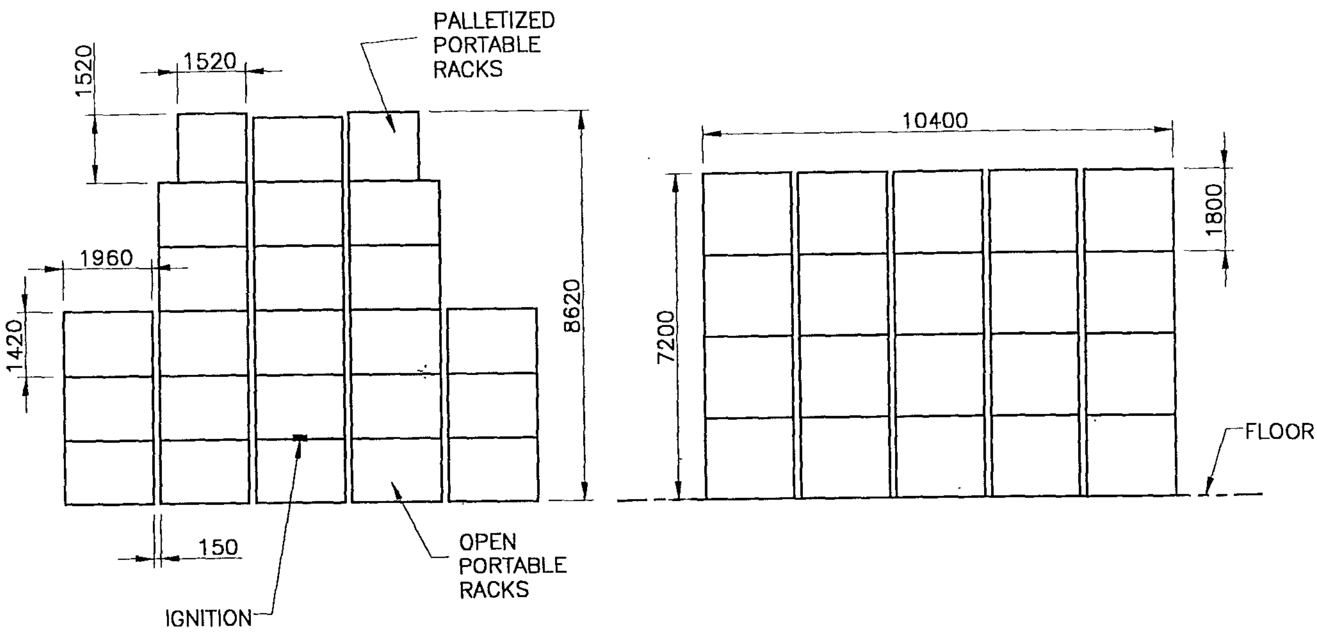
Three tests were conducted by Factory Mutual. The means of suppression for all tests was a large orifice (20mm) sprinkler array with 3.05m x 3.05m spacing and engineered to deliver a density of 24.5 l/min/m^2.[67] The sprinkler array was located at ceiling level at a height of 8.53m.

Test 1 involved "interlaced" automobile tyres stored on open portable metal racks. Each rack had dimensions of 1420mm x 1960mm x 1800mm. The individual racks were stacked together to form an array as shown in figure 9.3-1. The sprinkler system failed to control the fire. In total 77 sprinkler heads operated with a combined flow of 18,600 l/min. Structural steel ceiling temperatures reached 830^{0}C. A number of tyres fell out of the racks and thick black smoke was reported to have totally obscured the view of the fire after approximately 10.5 minutes.[67]

The second test involved truck tyres, bulk stacked on their side, to form a pyramidal arrangement as shown in figure 9.3-2. This configuration was controlled by the overhead sprinkler array. In brief, nine sprinklers operated, giving a combined flow of 2146 l/min. The ceiling structural size reached a peak temperature of 511^{0}C. [67]

In the third test, automobile tyres were stored in palletised portable boxes. These units were arranged to form a configuration as shown in figure 9.3-3. The overhead sprinkler was deemed to have failed in this test as the ceiling temperatures experienced in the structural steel were excessive. During the test 29 sprinkler heads operated giving a total flow of 7,000 l/min.[67]

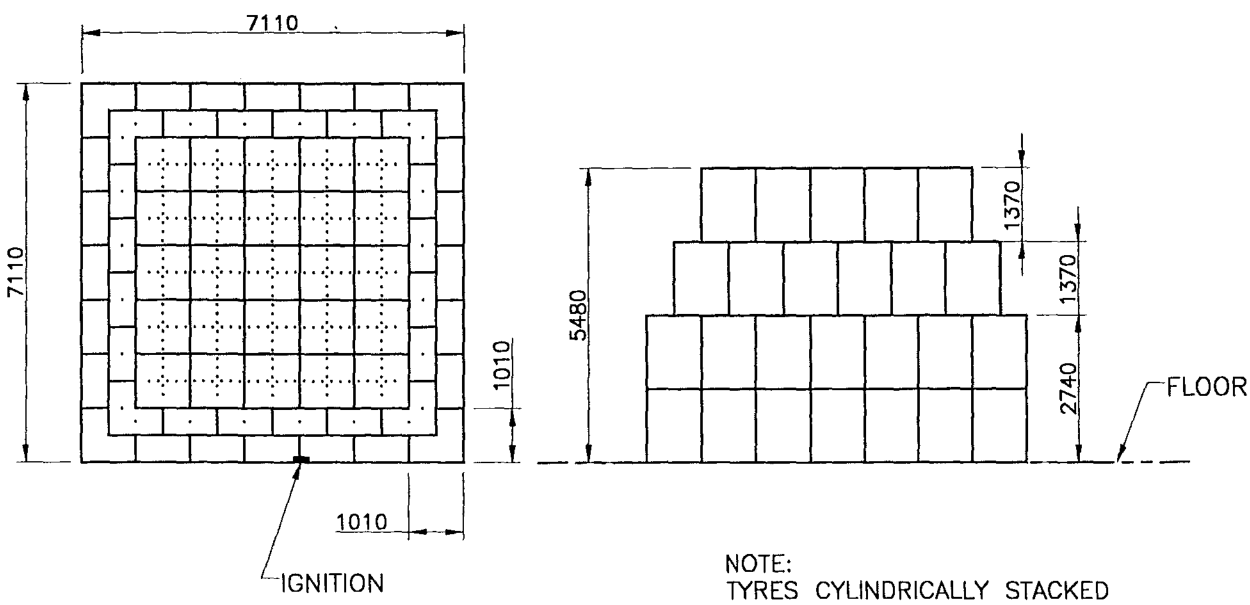
Figure 9.5-1: Tyre Storage Test Configuration - FMRC Test 1. [67]



Plan View

Elevation View

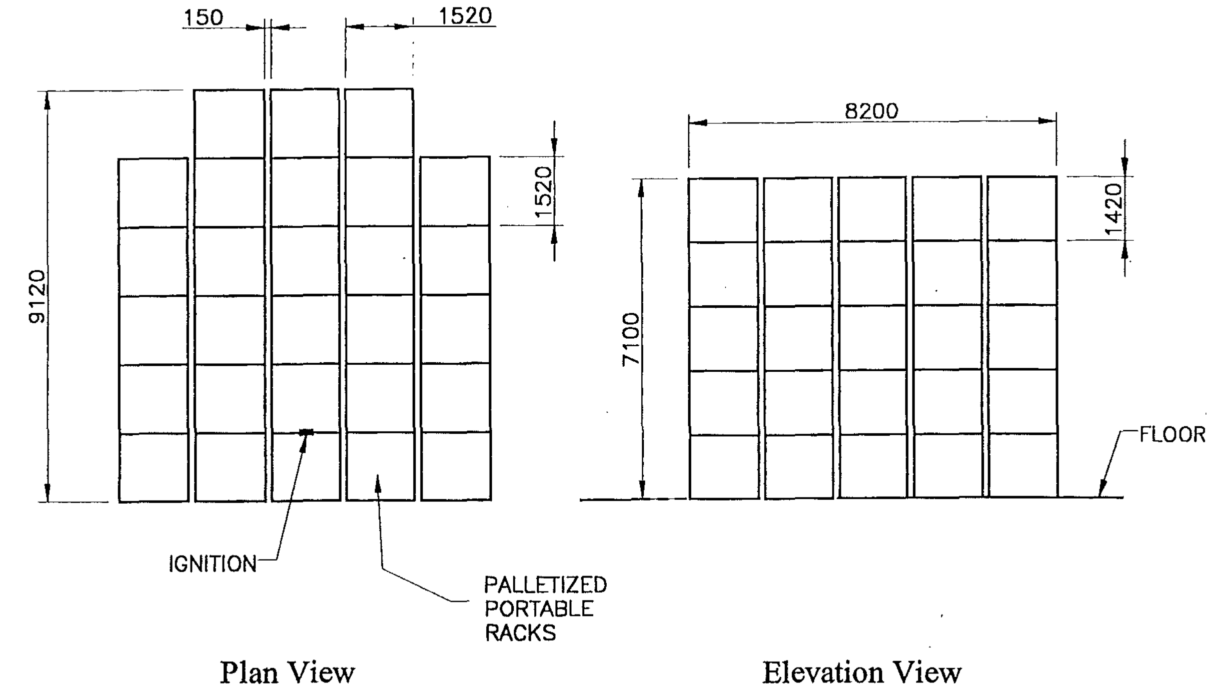
Figure 9.5-2: Tyre Storage Test Configuration - FMRC Test 2. [67]



Plan View

Elevation View

Figure 9.5-2: Tyre Storage Test Configuration - FMRC Test 3. [67]



The severe nature of stored rubber tyre fires as demonstrated by the Factory Mutual Corporation test results are reflected in the requirements of NFPA-231D. This standard requires a minimum water supply of three hours for the sprinkler system, plus an additional capacity of 2835 l/min for hose streams.[65] Appendix B of this standard addresses the issues of fire fighting in rubber tyre storage facilities protected with a sprinkler system. The document highlights that with approved densities the sprinkler system will only control the fire, extinguishment by the sprinklers alone will not occur. This section also warns about the need to wear breathing apparatus due to the thick black smoke that is quickly generated, and comments about the short time period required for structural roof temperatures to reach critical valves.[65]

Lawrence Livermore National Laboratory undertook a series of fire tests on stacked tyres.[68] The aim of the project was to conduct experiments to evaluate the effectiveness of various water based extinguishing agents.

Tests were performed in an enclosure with dimensions 6.1m x 3.96m x 4.57m. In addition to ventilation provided by an open door, forced ventilation was provided by a fan unit. The fuel load consisted of twelve automobile tyres that were stacked in a staggered configuration. The tyres were supported on a metal grate and encaged in wire mesh to prevent the array from collapsing.

Ignition was achieved by a gas burner located at low level. A standard fire fighting spray type nozzle was positioned and fixed to enable complete coverage of the stacked tyre array. This device was set to deliver 58 l/min at a pressure of 550 kPa.[68]

The extinguishing agent was applied intermittently, ie., one minute of application followed by a further two minutes to allow for the fire to redevelop. The extinguishing agent was reapplied for a period of one minute if the fire redeveloped. If the fire could not be controlled after three applications the extinguishing agent was deemed to have failed. The test series evaluated both class A and B type foam solutions.[68] Table 9.3-1 lists the results of the class A foam solutions tested, as detailed in the draft report.

Table 9.5-1: Draft Results of the Class A Type Foam Products Tested on Stacked Tyres.[68]

PRODUCT	CONCENTRATION %	EXTINGUISHED FIRE	NO. OF APPLICATIONS	MASS LOSS (KG)
Ansul - Silv-ex	0.3	Yes	3	2.30
Ansul - Silv-ex	0.6	No*	3	4.10
Chemonics-Fire-trol	0.3	Yes	3	3.70
Chemonics-Fire-trol	0.6	Yes	3	3.09

Notes: * Fire appeared to be out but rekindled after 4:00 minutes following the third application.

NIST researchers also undertook a series of tests to evaluate the effectiveness of foam based extinguishing agents.[64] A key objective of the study was to compare the results of the foam based extinguishing methods to those obtained using plain water.

The fire load consisted of nine tyres stacked in a 3 x 3 array. A small quantity of diesel fuel was used for ignition and pre-burn purposes. Suppression agents were applied through manual techniques, with the fire fighter having unrestricted access to the tyre array. A standard commercial jet spray nozzle was used to apply the agent at a flow rate of 30 l/min ($\pm$ 10%). The suppression agents were applied by three methods; spray application, aspirated nozzle application and through a CAF's system.[64] A summary of the results for the 1% solution applications with spray and aspirated nozzles are shown in table 9.5-2.

Table 9.5-2: NIST Stacked Tyre Fire Test Results - Summary for 1% Solution Applications.

AGENT	FLOW RATE l/min	EXPANSION RATIO	TIME TO SUPPRESSION (Sec)	TIME TO RE-IGNITION (Sec)
Spray Application Water †	30.3	-	286	364
1% Agent				
A	28	1.5	72	125
A	28	3.5	95	225
B	28.8	1.6	70	230
B	28.8	1.6	75	105
Average	28.4	2.05	78	171
Aspirated Nozzle Application 1% Agent				
A	31.1	4.6	75	85
A	31.1	4.6	110	70
B	31.1	5.4	85	185
B	31.1	5.4	111	None
Average	31.1	5.0	95	85

Note: †, the shown results for this extinguishing medium are based on the average of 5 repetitive tests.

Tests were also performed with a compressed air foam (CAF's) application. The average time for suppression with this application method was 73.5 seconds, while the average re-ignition time was 1140.5 seconds.[64]

The authors of the NIST study conclude that synthetic based extinguishing agents performed better than water.[64] This trend is also reconfirmed by the draft findings undertaken by researchers at the Lawerence Livermore National Laboratory.[68]

As previously detailed, full scale fire tests have shown that it is difficult to control a stored rubber tyre array with an overhead sprinkler system.[67] Manual fire fighting tests, as described above, have demonstrated that the application of class A foam to a rubber tyre fire is more effective than water. This combined evidence suggests that the addition of class A foam to sprinkler systems would enhance their effectiveness. The use of this technology would be dependent on the favourable outcome of scientifically based tests being performed to establish fire fuel load and density parameters.

CHAPTER 10.0 RECOMMENDATIONS AND CONCLUSIONS

10.1 General Conclusions

Only a minimum amount of information has been published relating to class A foam-water sprinkler systems. Tests undertaken with residential fuel packages, demonstrated that a class A foam based sprinkler system had superior suppression properties compared to a water based system.[7] Similar findings resulted when full scale tests on vertically stacked polypropylene plastic boxes were conducted.[8, 9]

Tests conducted with a specifically engineered compressed air foam sprinkler system also showed superior suppression performance, when evaluated against standard sprinklers and water mist technology.[10] Researchers investigating the fire suppression performance properties of class A foam for use in manual fire fighting, report conflicting conclusions, with most recommending further testing.

The research programme conducted by NIST[19] highlighted some favourable characteristics of class A foam such as the:-

- Mass retention on porous materials.
- Improved suppression of polycyclic aromatic hydrocarbons present in smoke emissions.

The NIST[19] tests showed there to be very little difference compared to water with regards to:-

- The heat release rate and suppression effectiveness on a wood crib fire.
- Decomposition gas concentration suppression.
- Ignition - inhibition.

Plain water was found to have superior properties than class A foam with regards to:-

- Mass retention on non-porous materials.
- The size and distribution range of smoke particles produced.[19]

A key characteristic of class A foam solution is it's reduced surface tension characteristics. This property accounts for the high penetration rates and increased surface contact angle. These features give class A foam excellent wetting properties and suggest that it's use is most suited to deep seated class A fires. Recent theories relating to foam stability,[44] state that, typical low expansion foam as produced by a class A foam sprinkler systems, will produce a finished foam with a large distribution of bubble sizes which will have a high diffusion rate. This theory suggests that the use of this technology is not appropriate if the specific fuel being protected requires a stable foam.

A literature review relating to environmental issues suggests that the use of this technology will not pose a threat to the environment if the appropriate steps are taken at the design and implementation phase. Research has shown that some products are readily biodegradable while others are not, hence care must be taken when selecting concentrates. Data is available to access the likely impact on a cross section of aquatic species. Some researchers have claimed that the use of class A foam as opposed to pure water could potentially do less environmental damage.[48] This assumption is based on the applied densities being reduced and therefore the quantity of contaminated run off water reduced. Local environmental authorities and waste treatment plant should be consulted prior to installing a system.

Hardware solutions already exist for the storage, transferring and proportioning of class A foam and the integration with a wet pipe sprinkler system. Care should be taken when selecting hardware materials in order to ensure compatibility with the proposed type of foam.

A number of potential applications are feasible with this technology. It is envisaged that the use of class A foam in sprinkler systems would be "risk specific". "Risk specific" implies that there use would be limited to the protection of specific fire load commodities and configurations that had undergone sound scientific tests to determine suppression performance and limitations. The results of previously successful fire tests indicate that this technology has the potential to protect extreme hazard class A type commodity fires, such as the protection of certain plastic and rubber products. The implementation of this technology could also offer advantages in limited water supply situations if it was found that the applied density could be reduced without lowering the overall integrity of the system.

Tests conducted in this project, showed that a slight increase in the foam expansion ratio, occurred as the applied head pressure was increased from 50 to 85kPa. Further expansion ratio increases were not obtained with higher head pressures. It is uncertain if these elevated pressure results indicate a true characteristic trend of class A foam sprinkler systems, or if the results obtained where influenced by the limiting performance of the pump unit used. The expansion ratios obtained were very similar to previous tests conducted with 3% AFFF, using the same type of sprinkler at similar pressures.[40]

The tests undertaken revealed near instantaneous drain times. The distribution tests showed that the overall minimum density requirement in accordance with UL standard 199 could be achieved. The overall density values obtained were similar to previous tests conducted using plain water. Large density variations occurred when the contents of identically positioned collection trays within the array were compared. Based on the results obtained, it can be concluded that the addition of class A foam solution to a sprinkler system, does not have any adverse detrimental effects on the distribution coverage patterns of standard type sprinkler heads.

10.2 Future Research

As previously mentioned, it is envisaged that this technology could prove to be appropriate in the protection of extreme hazard class A fires such as the storage of rubber tyres and certain plastic products. The established success of a limited number of tests undertaken with such materials suggests that this area would be a logical starting point for future research.[64, 68]

In selecting suitable fire materials to test, consideration should be given to the beneficial properties offered by class A foam such as, reduced surface tension, wetting and penetration ability. The researcher should determine what likely effects these properties will have on the protection of porous or non-porous materials with the orientation proposed.

Laboratory tests need to be undertaken to determine if class A foam solution will have any detrimental corrosion effects on certain (untested) materials typically used in a sprinkler system.

In the evaluating the suitability of utilising this technology to protect stored rubber tyre installations, preliminary testing needs to be conducted in order to justify doing large scale tests. Preliminary fire tests could be based on protecting a typical palletized portable rack unit as detailed in NFPA-231D.[65] These racks typically store 30-40 tyres. Tests should be undertaken with an overhead sprinkler array with head spacing based on an extra high hazard requirement. Due to the particular nature of the smoke and residue products associated with such a fuel, tests would best be performed in an open air facility. The testing apparatus should include a sand bed or other suitable residue collection medium as utilised in the NIST tests.[64] A partial enclosure over the tyre rack could be used to support the sprinkler array and allow for a limited number of thermocouples to be located.

The tyre rack could be ignited and the fire allowed to develop to a stage where it is anticipated that temperatures would have operated heads in a full height storage situation. Tests should be performed to determine what critical application density of class A solution is required to extinguish the fire load. Equivalent densities should be applied with pure water and evaluations made of the two extinguishing mediums.

In addition to varying the density, a range of head pressures should be tried to see if this parameter has any bearing on suppression capabilities. The effects of radiation heat transfer could be assessed by locating additional tyre storage racks adjacent to the "test rack". The separation distance between these units should be based on standard tyre storage array spacings.

If such tests prove to be beneficial, full scale tests similar to those conducted by Factory Mutual to determine NFPA-231D requirements, should be undertaken.[67] For such tests, it is envisaged that the applied density would be based on the critical density determined in the preliminary tests and include a suitable safety margin.

REFERENCES

1 NFPA 16A (1994): Installation of Closed Head Foam Water Sprinkler Systems. National Fire Protection Association, Quincy, MA.

2 Colletti, D.J. (1998). Personal Correspondence.

3 Mulhaupt, R. (1998). Personal Correspondence. National Fire Protection Association Research Foundation, Quincy Massachusetts.

4 Ansul (1997). Silv-ex "Class A Foam Concentrate". Ansul Incorporated, Marinette, WI.

5 National Foam (1998). "Litewater" (Foam Application Manual). National Foam Corporation.

6 Carey, W: (1994): National Class A Foam Research Project Technical Report. Structural Fire Fighting Room Burn Tests Phase II. National Fire Protection Research Foundation.

7 Carey, W.M. (1995). Report of Sprinkler Research, Contract EMW-94-R-4499, prepared for Federal Emergency Management Agency, United States Fire Administration, Underwriters Laboratories Inc., Project 94Nk25391/USNC226, Northbrook, Illinois.

8 Nett, H. and Hennecke, M. (1996). Brandund Löschversuch im Hochregallager mit Sprinkleranlage und Schaumzumischung Silv-ex G an KLT[1] Behaltem aus Polypropylene nach DIN 30820 und VDA-Empfehling 4500. (Fire and Extinguishing Tests on Racks Loaded with KLT (small plastic boxes) and Sprinkler System containing Silv-ex-G Foam Concentrate, to DIN 30820 and VDA Recommendation 450). Total Walther Germany.

9 Brand-und Loschversuche in Hoch-regallager mit sprinkleranlagen an kLT-Benaltern aus Polypropylene nach DIN 30820 und VDA-Empfehling 4500 (Fire and Extinguishing Tests on Racks Loaded with kLT (small plastic boxes) and Sprinkler Systems to DIN 30820 and VDA 4500). Total Walther Germany.

10 Kim, K.A. and Dlugogorski, B.Z (1997). Multipurpose Overhead Compressed-Air Foam System and its Fire Suppression Performance. National Fire Laboratory. Institute for Research and Construction. National Research Council Canada. Journal of Fire Protection Engineering 8(3), 1977 pp 113-150.

11 Colletti, D.J. (1993) Quantifying the effects of Class A foam in Structural Fire Fighting, (The Salem Tests). Fire Engineering February 1993.

12 Colletti, D.J. (1992). Class A Foam for Structural Fire Fighting. Fire Engineering July 1992.

13 Bosley, K. (1997). Water Additives for Fighting Class A Fires. Research Report Number 3/98. Home Office Fire Research and Development Group. London U.K.

14 Drysdale, D.D. and Grant, G.B. (1997). The Suppression and Extinction of Class A Fires using Water Sprays. University of Edinburgh. Home Office Fire Research and Development Group. London U.K. p 169.

15 Pabich, M.J. and Carey, W.M. (1997). Technical Report on Delivery and Suppression Performance Evaluation of Class A Foam. Prepared by Underwriters Laboratories Inc., Project 96NK 29338/US262.

16 de Vries, H. The use of new foams and foam equipment against solid fuel fires. University of Wuppertal.

17 Gravestock, N. (1998). Full Scale Testing of Fire Suppression Agents on Shielded Fires. University of Canterbury.

18 Carey, W.M. (1994). Structural Fire Fighting - Room Burn Tests Phase II. National Class A Foam Research Project Technical Report. Prepared by Underwriters Laboratories Inc., for National Fire Protection Research Foundation.

19 Madrzykowski, D. and Stroup, D.W. (1998). Demonstration of Biodegradable Environmentally Safe, Non-Toxic Fire Suppression Liquids (NISTIR 6191) U.S. Department of Commerce Technology Administration, National Institute of Standards and Technology, Gaithersburg, M.D.

20 Josler, W.J. (1998). Demonstration of Biodegradable Environmentally Safe, Non-Toxic Fire Suppression Liquids (NISTIR 619) U.S. Department of Commerce Technology Administration, National Institute of Standards and Technology, Gaithersburg, M.D., Chapter 3, Fire Exposure Protection. pp 3-1 to 3-36.

21 Bryner, N.P. (1998). Demonstration of Biodegradable Environmentally Safe, Non-Toxic Fire Suppression Liquids (NISTIR 619) U.S. Department of Commerce Technology Administration, National Institute of Standards and Technology, Gaithersburg, M.D., Chapter 4, Smoke Characterisation. pp 4.1 to 4.52.

22 Madrzykowski, D. and Stroup, D.W. (1998). Demonstration of Biodegradable Environmentally Safe, Non-Toxic Fire Suppression Liquids (NISTIR 619) U.S. Department of Commerce Technology Administration, National Institute of Standards and Technology, Gaithersburg, M.D., Chapter 5, Class A Fire Suppression Experiments. pp 5-1 to 5-22.

23 Takahashi, S. (1993). Extinguishment of Plastic Fires with Plain Water and Wet Water. Fire Research Institute, Tokyo, Japan. Fire Safety Journal 22 (1994), pp 169-179.

24 Wahl, A.M. (1997). Water and Water Additives for Fire Fighting. Fire Protection Handbook - Eighteenth Edition. National Fire Protection Association, Quincy, Massachusetts. pp 6-5, - 6-7.

25 Dundas, P.H. (1974). Optimization of Sprinkler Fire Protection, Progress Report No. 10. The Scaling of Sprinkler Discharge: Prediction of Drop Size, FMRC No. 18792, Factory Mutual Research Corp., Norwood, MA., June 1974.

26 Chow, Wik and Shet, L.C. (1993). Physical Properties of a Sprinkler Water Spray. Department of Building Services Engineering, Hong Kong Polytechnic, Hong Kong. Fire and Materials, Vol. 17. pp 279-292.

27 Prahl, J.M. and Wendt, B. (1988). Discharge Distribution Performance for an Axisymmetric Model of a Fire Sprinkler Head. Department of Mechanical and Aerospace Engineering, Case Western Reserve University, Cleveland. Fire Safety Journal, 14 (1988). pp 101-111.

28 Kumar, S., Haywood, G.M. and Liew, S.K. (1997). Superdrop Modelling of a Sprinkler Spray in a Two Phase CFD-Particle Tracking Model. Fire Research Station, Watford, U.K. International Symposium on Fire Safety Science (5th, 1977 World Congress Centre, Melbourne).

29 Solomon, R.E. (1997). Automatic Sprinkler Systems. Section 6, Chapter 10. Fire Protection Handbook - Eighteenth Edition. National Fire Protection Association, Quincy, Massachusetts. pp 6-154.

30 Flemming, R.P. (1997). Theory of Automatic Sprinkler Performance. Section 6, Chapter 8 - Fire Protection Handbook - Eighteenth Edition. National Fire Protection Association, Quincy, Massachusetts. pp 6-113 - 6-123.

31 Isman, K.E. (1997). Automatic Sprinklers. Section 6, Chapter 9, Fire Protection Handbook - Eighteenth Edition. National Fire Protection Association, Quincy, Massachusetts, p 6-24.

32 Underwriter Laboratories Standard UL-199 (1997). Automatic Sprinklers for Fire Protection Service. Underwriters Laboratories Inc. pp 31-33.

33 Nash, P. and Young, R.A. (1991). Automatic Sprinkler Systems for Fire Protection, 2nd Edition. pp 25-41.

34 Evans, D. (1993). Sprinkler Fire Suppression Algorithm for HAZARD. Building and Fire Research Laboratory. National Institute of Standards and Technology.

35 Walton, W.D. (1988). Suppression of Wood Crib Fires with Sprinkler Sprays: Test Results. NBSIR 88-39-696. U.S. Department of Commerce. National Bureau of Standards.

36 Johnson, C.W. and George, C.W. (1997). USDA Forest Service: Wildland, Fire Foam Characterisation, National Wildfire Suppression Technology Programme, Intermountain Fire Service Laboratory, Missoula, Montanna (Table 8).

37 Colletti, D.J. (1992). Class A Foam for Structural Firefighting. Fire Engineering, July 1992.

38 Gardiner, B.S., Dlugogorski, B.Z., and Jamieson, G.J. (1998). Rheology of Firefighting Foams. Department of Chemical Engineering, The University of Newcastle, Australia. Fire Safety Journal 1998. p2.

39 Stroup, D.W., and Madrzykowski, D., and Bishop, M.J., (1998). Demonstration of Biodegradable, Environmentally Safe, Non-Toxic Fire Suppression Liquids, Chapter 2 Fire Fighting Properties. Report No. NISTIR 6191. National Institute of Standards and Technology. pp. 2-2 - 2-24.

40 Scheffey, J.L. (1997). Foam Agents and AFFF System Design Considerations. The SFPE Handbook of Fire Protection Engineers 2nd Edition. Society of Fire Protection Engineers / National Fire Protection Association. pp 4-70 to 4-98.

41 Ansul (1997). Foam System Design and Applications. Ansul Incorporated, Marinette, WI. pp 3-1.

42 NFPA-11 (1998). Standard for Low Expansion Foam. National Fire Protection Association, Quincy, Massachusetts.

43 Cowan, G. (1995): Wave of Future is Class A Foam. Fire Fighting in Canada, March 1995.

44 Kim, A.K. and Dlugogorski, B.Z. (1997). Multipurpose Overhead Compressed-Air Foam System and its Fire Suppression Performance. National Fire Laboratory Institute for Research in Construction. National Research Council, Canada. Journal of Fire Protection Engineering, Vol. 8, No. 3, 1997. pp 133-150.

45 Factory Mutual Research Corporation (1993). File Ex1226, 16 Pan Distribution Tests, Model A Pendant. pp T13-3 to T13-4.

46 NFPA 298 (1994): Fire Fighting Foam Chemical for Class A Fuels in Rural, Suburban and Vegetated Areas. National Fire Protection Association, Quincy, MA.

47 Johnson, C.W., and George, C.W. (1997) USDA Forest Service: Wildland Fire Foam Characterisation, National Wildfire Suppression Technology Programme, Intermountain Fire Service Laboratory Missoula, Montana.

48 de Vries, H. (1998): The Use of New Foams and Foam Equipment Against Solid Fuel Fires, University of Wuppertal, Germany; p16-17.

49 Whiteley, B. (1994): Fire Fighting Effects on the Environment, Fire International, August-September 1994; pp 35-36.

50 Finger, S. (1995): Environmental Implications of Firefighting Chemicals, United States Department of Interior, National Biological Service Columbia. National Wildfire Co-ordinating Group. P 4-6.

51 ANSUL: Foam and the Environment, Technical Bulletin, No. 60; ANSUL Incorporated Marinette, WI 1997.

52 Marryatt, H.W. (1988); A Century of Automatic Sprinkler Protection in Australia and New Zealand 1886-1986; p 91.

53 Wieneke, A: Erarbeitung von Konzepten zur Beurteiling und Reiningung kontanimierter Löschwässer (Dissertation). Fortschritt-Berichte VDI Reihe 15 Nr. 166 VDI Verlag Düsseldorf Germany 1997.

54 Notarianni, K.A., and Jackson, M.A.: (1994) Comparison of Fire Sprinkler Piping Materials: Steel, Copper, Chlorinated Polyvinyl Chloride and Polybutylene, in Residential and Light Hazard Installations. Building and Fire Research Laboratory. National Institute of Standards and Technology. Gaithersburg. pp 8-11.

55 Bshart, T.K. (1998) Detection, Treatment and Prevention of Microbiologically Influenced Corrosion in Water Based Fire Protection Systems. National Fire Sprinkler Association, INC., New York.

56 Hubert, M (1999). Personal Correspondence - Ansul Incorporated.

57 Factory Mutual System (1995) Roll Paper Storage Loss Prevention Data 8-21. Factory Mutual Engineering Corporation, pp. 1-14.

58 Scoones, K. (1997). Serious Fires in the Paper Packaging and Print Industries during 1995. Fire Protection Association - UK. Fire Prevention December 1997, pp. 36-37.

59 NFPA 231F (1996). Standard for the Storage of Roll Paper. National Fire Protection Association, Quincy, Massachusetts.

60 Smith, P.A. (1980). A Full-Scale Roll paper Fire-Test Programme. Fire Journal - September 1980.

61 Mawhinney, J.R. (1990). The Hagersville Tire Fire, February 12 to 28, 1990. National Research Council Canada Report No. 593.

62 Cohn, B.M. (1996). Plastics and Rubber National Fire Protection Association Handbook 18th Edition, p. 4-123.

63 Society of Fire Protection Engineers Handbook of Fire Protection Engineering 2nd Edition. p. - A44.

64 Madrzykowski, D., and Strap, D. (1998). Class A Fire Suppression Experiments. Demonstration of Biodegradable Environmentally Safe, Non-Toxic Fire Suppressions Liquids. National Institute of Standards and Technology. pp. 5-1 - 5-22.

65 NFPA 231D (1994). Standard for the Storage of Rubber Tires. National Fire Protection Association, Quincy, Massachusetts.

66 Johnson, B.P. (1992). Additives for Hosereel Systems: Trials of Foam on Tyre Fires. Fire Research and Development Group, Home Office, UK.

67 Dean, R. (1993) Rubber Tires: Investigation of a Common Protection for three types of Storage. Factory Mutual Research Corporation, Norwood, Massachusetts (FMRC J.I. OW1R3.RR).

68 Hasegawa, H.K., and Staggs, K.J. (1990). Draft - Large Scale Tests to Evaluate the Effectiveness of Various Fire Suppression Agents on Burning stacked Tires. Lawrence Livermore National Laboratory, Livermore.

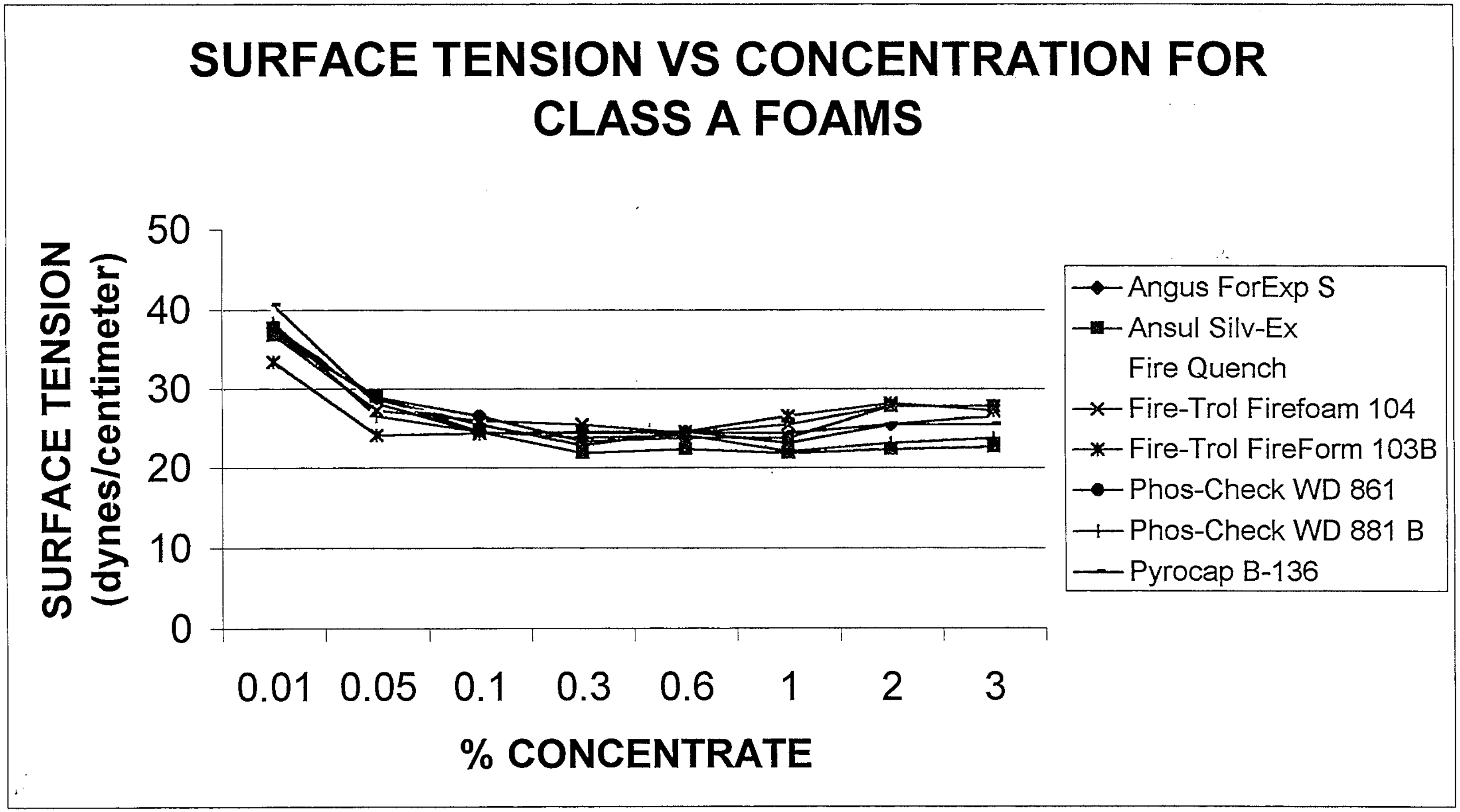
Appendix 1 Physical Properties

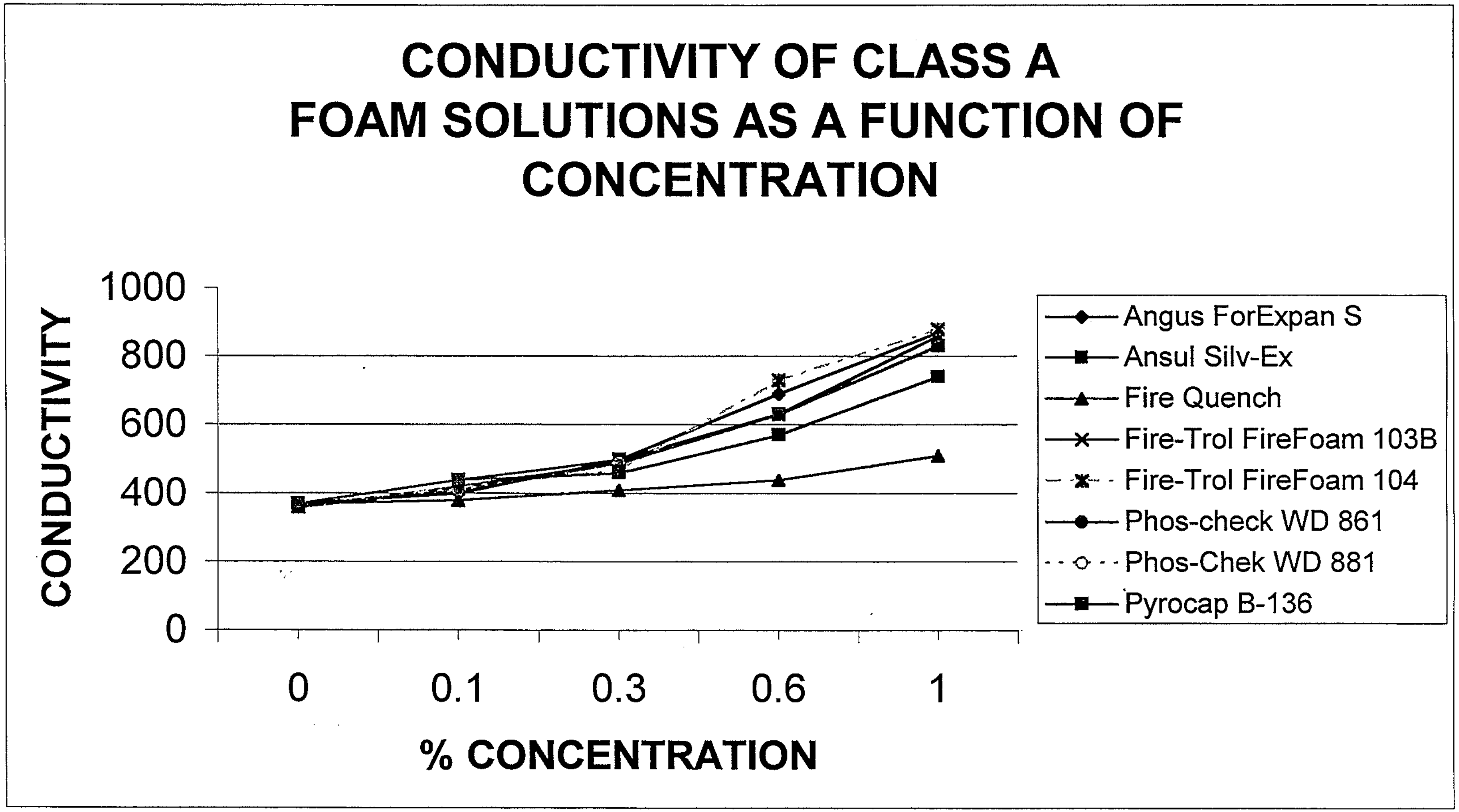
Physical Properties of various Class A Foam Concentrates at Room Temperature.

Product	Vapour(a) Pressure (kPa)	Viscosity(b) (Centipose)	Density(c) g/cm^3	pH
Angus ForeExps	4.1	30	1.042	7.3
Ansul Silv-Ex	4.1	25	1.010	7.9
Fire Quench	6.9	385	1.024	7.8
Fire-Trol Firefoam 104	6.9	32	1.010	6.6
Fire-Trol Firefoam 103B	3.5	48	1.028	8.9
Phos-Check WD 861	4.1	49	1.026	7.8
Phos-Check WD 881	6.9	52	1.029	7.2
Pyrocap B-136	6.20	145	1.037	8.1
Average	**5.34**	**95.75**	**1.026**	**7.7**

Source - Data was collected from the various tables in Johnson, C.W., and George, C.W. [47]
Values have been converted to metric unit as required.

Notes
(a) Based on ASTMD-323 Reid Method.
(b) Valves obtained with Brookfield Model LVF Viscometer and sprindle No. 2.
(c) Valves obtained with Mettler/Parr density meter.


SURFACE TENSION VS CONCENTRATION FOR CLASS A FOAMS
SURFACE TENSION (dynes/centimeter)
50
40
30
20
10
0
0.01
0.05
0.1
0.3
0.6
1
2
3
% CONCENTRATE
Angus ForExp S
Ansul Silv-Ex
Fire Quench
Fire-Trol Firefoam 104
Fire-Trol FireForm 103B
Phos-Check WD 861
Phos-Check WD 881 B
Pyrocap B-136


CONDUCTIVITY OF CLASS A FOAM SOLUTIONS AS A FUNCTION OF CONCENTRATION
CONDUCTIVITY
1000
800
600
400
200
0
0
0.1
0.3
0.6
1
% CONCENTRATION
Angus ForExpan S
Ansul Silv-Ex
Fire Quench
Fire-Trol FireFoam 103B
Fire-Trol FireFoam 104
Phos-check WD 861
Phos-Chek WD 881
Pyrocap B-136

Appendix 2 Environmental Properties

Toxicity of various Class A foam solutions formulated at 1% concentration.
(Source - adapted from Johnson, C.W. and George, C.W.[47])

Product	Acute Oral LD_{50}	Acute Dermal LD_{50}	Skin Irritation	Eye Irritation Unwashed Eyes	Eye Irritation Washed Eyes
Requirement	>5000 mg/Kg	>2000 mg/Kg	P.I. Score:<5.0	<Mildly Irritating	<Mildly Irritating
Angus ForExpan S	>5050 mg/Kg	>2020 mg/Kg	P.I. score: 0.7 Slightly irritating Toxicity category IV	Minimally irritating Irritation Score: 3.7 Toxicity category IV	Minimally irritating Irritation Score: 6.0 Toxicity Category III
Ansul Silv-Ex	>5050 mg/Kg	>2020 mg/Kg	P.I. score: 0.4 Slightly irritating Toxicity category IV	Minimally irritating Irritation Score: 4.0 Toxicity category III	Minimally irritating Irritation score: 6.0 Toxicity category III
Fire Quench	>5050 mg/Kg	>2020 mg/Kg	P.I. score: 0.1 Slightly irritating Toxicity category IV	Minimally irritating Irritation score: 8.3 Toxicity category III	Minimally irritating Irritation score: 8.0 Toxicity category III
Fire-Trol FireFoam 103B	>5050 mg/Kg	>2010 mg/Kg	P.I. score: 0.3 Slightly irritating Toxicity category IV	Minimally irritating Irritation score: 4.0 Toxicity category III	Minimally irritating Irritation score: 4.7 Toxicity category III
Fire-Trol Fire Foam 104A	>5050 mg/Kg	>2020 mg/Kg	P.I. score: 0.5 Slightly irritating Toxicity category IV	Minimally irritating Irritation score: 5.3 Toxicity category III	Minimally irritating Irritation score: 5.3 Toxicity category III
Phos-Chek WD 861	>5000 mg/Kg	>2000 mg/Kg	P.I. score: 0.3 Slightly irritating Toxicity category IV	Minimally irritating Irritation score: 7.3 Toxicity category IV	Minimally irritating Irritation score: 10.0 Toxicity category IV
Phos-Chek WD 881	>5000 mg/Kg	>2000 mg/Kg	P.I. score: 0.3 Slightly irritating Toxicity category IV	Minimally irritating Irritation score: 2.0 Toxicity category III	Practically non-irritating Irritation score: 2.0 Toxicity category IV
Pyrocap B-136	>5050 mg/Kg	>2020 mg/Kg	P.I. score: 0.3 Slightly irritating Toxicity category IV	Minimally irritating Irritation score: 3.0 Toxicity category IV	Minimally irritating Irritation score: 4.0 Toxicity category IV

Key for Skin Irritation Tests

Primary Irritation Descriptive Rating (P.I.)	
Descriptive Rating	**Primary Irritation Index**
Non irritating	0.0
Slighting irritating	0.1-1.9
Moderately irritating	2.0-5.0
Severely irritating	5.1-8.0

Dermal Irritating Toxicity Categories (40 CFR 162.10)	
Toxicity Category	**Irritation Level at 72 Hours**
I	Corrosive
II	Severe Irritation
III	Moderate Irritation
IV	Mild or slight irritation

Key to Toxicity Ratings for Eye Irritation Tests

Rating Category	Average Score	Category Description
Non-irritating	0.0-0.5	All scores must be zero at 24 hours; otherwise, increase category one level
Practically Non-irritating	0.5-2.5	All scores must be zero at 24 hours; otherwise, increase category one level
Minimally irritating	2.5-15.0	All scores must be zero at 72 hours; otherwise, increase category one level
Mildly irritating	15.0-25.0	All scores must be zero at 7 days; otherwise, increase category one level
Moderately irritating	25.0-50.0	Scores must be ≤10 for 60% or more of the rabbits. The mean score at 7 days must be ≤20. If the 7-day mean score is ≤20, but <60% of rabbits have scores <10, then no rabbit can have a score >30; otherwise, increase category one level
Severely irritating	50.0-80.0	Scores must be ≤30 for 60% or more of the rabbits. The mean score at 7 days must be ≤40. If the 7-day mean score is ≤40, but <60% of rabbits have scores <30, then no rabbit can have a score >60; otherwise, increase category one level
Extremely irritating	80.0-110.0	

Eye Irritation Toxicity Categories

Category	Descriptive Criteria for Eye Irritation Ratings
I	Corrosive (irreversible destruction of ocular tissue) or corneal involvement or conjunctival irritation persisting through Day 21.
II	Corneal involvement or conjunctival irritation clearing in 8-21 days.
III	Corneal involvement or conjunctival irritation clearing in 7 days or less.
IV	Minimal effects clearing in less than 24 hours.

Summary of the "aerobic aquatic" and "ready Biodegradability" tests for serial Class A foam solutions.
(Source - adapted from Johnson, C.W. and George, C.W.[47])

Product	Aerobic Aquatic Biodegradability[1]	Ready Biodegradability Closed Bottle Test[2]
Angus ForExpan S	Not Biodegradable	Readily Biodegradable $\geq$ 60% at 28 days
Ansul Silv-Ex	Readily Biodegradable 100% DOC at 28 days	Readily Biodegradable $\geq$ 60% at 28 days
Fire Quench	Not Biodegradable	Readily Biodegradable $\geq$ 60% at 28 days
Fire-Trol FireFoam 103B	Not Biodegradable	Not Biodegradable < 45% at 28 days
Phos-Check WD 881	Not Biodegradable	Readily Biodegradable $\geq$ 60% at 28 days
Pyrocap B-136	Partially Biodegradable 27% DOC at 28 days	Not Biodegradable $\geq$ 60% at 28 days

[1] Results of the aerobic aquatic biodegradability tests are based on the initial dissolved oxygen content.

[2] Results of the ready biodegradability tests have been corrected for the amount of water in the concentrate.

Toxicity of various Class A foam concentrates to Rainbow trout, at various life stages, for 96-HrLC50[2] at each life stage.
(Source - adapted from Johnson, C.W. and George, C.W.[47])

Product	Egg mgs/litre	Embryo larvae mgs/litre	Swim-up fry mgs/litre	60 DPH[3] mgs/litre	90 DPH[3] mgs/litre
Angus ForExpan S				22[4]	
Ansul Silv-Ex	>78	15	20	22	22
Fire Quench				39[4]	
Fire-Trol FireFoam 103B				12[4]	
Fire-Trol FireFoam 104				13[4]	
Phos-Chek WD 881	44	13	13	15	20
Pyrocap B-136				156[4]	

[1] Testing was performed by National Biological Service at Yankton, SD.
[2] ASTM soft water was used for all of the tests.
[3] DPH = days post hatch; a deviation from nominal of ± 15 days is acceptable.
[4] These tests were performed in 1996. The remaining tests were performed in 1993.

FIRE ENGINEERING RESEARCH REPORTS

95/1	Full Residential Scale Backdraft	I B Bolliger
95/2	A Study of Full Scale Room Fire Experiments	P A Enright
95/3	Design of Load-bearing Light Steel Frame Walls for Fire Resistance	J T Gerlich
95/4	Full Scale Limited Ventilation Fire Experiments	D J Millar
95/5	An Analysis of Domestic Sprinkler Systems for Use in New Zealand	F Rahmanian
96/1	The Influence of Non-Uniform Electric Fields on Combustion Processes	M A Belsham
96/2	Mixing in Fire Induced Doorway Flows	J M Clements
96/3	Fire Design of Single Storey Industrial Buildings	B W Cosgrove
96/4	Modelling Smoke Flow Using Computational Fluid Dynamics	T N Kardos
96/5	Under-Ventilated Compartment Fires - A Precursor to Smoke Explosions	A R Parkes
96/6	An Investigation of the Effects of Sprinklers on Compartment Fires	M W Radford
97/1	Sprinkler Trade Off Clauses in the Approved Documents	G J Barnes
97/2	Risk Ranking of Buildings for Life Safety	J W Boyes
97/3	Improving the Waking Effectiveness of Fire Alarms in Residential Areas	T Grace
97/4	Study of Evacuation Movement through Different Building Components	P Holmberg
97/5	Domestic Fire Hazard in New Zealand	KDJ Irwin
97/6	An Appraisal of Existing Room-Corner Fire Models	D C Robertson
97/7	Fire Resistance of Light Timber Framed Walls and Floors	G C Thomas
97/8	Uncertainty Analysis of Zone Fire Models	A M Walker
97/9	New Zealand Building Regulations Five Years Later	T M Pastore
98/1	The Impact of Post-Earthquake Fire on the Built Urban Environment	R Botting
98/2	Full Scale Testing of Fire Suppression Agents on Unshielded Fires	M J Dunn
98/3	Full Scale Testing of Fire Suppression Agents on Shielded Fires	N Gravestock
98/4	Predicting Ignition Time Under Transient Heat Flux Using Results from Constant Flux Experiments	A Henderson
98/5	Comparison Studies of Zone and CFD Fire Simulations	A Lovatt
98/6	Bench Scale Testing of Light Timber Frame Walls	P Olsson
98/7	Exploratory Salt Water Experiments of Balcony Spill Plume Using Laser Induced Fluorescence Technique	E Y Yii
99/1	Fire Safety and Security in Schools	R A Carter
99/2	A Review of the Building Separation Requirements of the New Zealand Building Code Acceptable Solutions	J M Clarke
99/3	Effect of Safety Factors in Timed Human Egress Simulations	K M Crawford
99/4	Fire Response of HVAC Systems in Multistorey Buildings: An Examination of the NZBC Acceptable Solutions	M Dixon
99/5	The Effectiveness of the Domestic Smoke Alarm Signal	C Duncan

99/6	**Post-flashover Design Fires**	**R Feasey**
99/7	**An Analysis of Furniture Heat Release Rates by the Nordtest**	**J Firestone**
99/8	**Design for Escape from Fire**	**I J Garrett**
99/9	**Class A Foam Water Sprinkler Systems**	**D B Hipkins**
99/10	**Review of the New Zealand Standard for Concrete Structures (NZS 3101) for High Strength and Lightweight Concrete Exposed to Fire**	**M J Inwood**
99/11	**Simple Empirical Method for Load-Bearing Light Timber Framed Walls at Elevated Temperatures**	**K H Liew**
99/12	**An Analytical Model for Vertical Flame Spread on Solids: An Initial Investigation**	**G A North**
99/13	**Should Bedroom Doors be Open or Closed While People are Sleeping? - A Probabilistic Risk Assessment**	**D L Palmer**
99/14	**Peoples Awareness of Fire**	**S J Rusbridge**
99/15	**Smoke Explosions**	**B J Sutherland**
99/16	**Reliability of Structural Fire Design**	**JKS Wong**

School of Engineering
University of Canterbury
Private Bag 4800, Christchurch, New Zealand

Phone 643 364-2250
Fax 643 364-2758